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The General Secretary read the minutes of the previous meeting, which were confirmed and signed as a correct record.

The President then introduced Mr Cameron, who presented the following paper in summary.

QUEEN ELIZABETH ISLANDS OF ARCTIC CANADA AND THEIR PETROLEUM PROSPECTS *

By A. BRYCE CAMERON †

SUMMARY

The Queen Elizabeth Islands have a great variety of geological formations with abundant signs of petroleum substances. There are many large closed structures similar in size to those in the Middle East. Geological field work has supported photoanalytical and photogrammetrical studies. Continuous drilling throughout the year might cost $2,000,000, with a proportionately reduced expenditure if no mid-winter operations were conducted. All the equipment could be shipped direct from Great Britain to beaches on the islands.

Rapid development could occur, with some oil being exported by tanker direct to West European and East Canadian markets within a year of discovery. Later a shuttle service should be able to carry oil during a four-month season to intermediate storage in Southwest Greenland, whence it could be transported throughout the year to world markets.

GENERAL

Physiography

The Queen Elizabeth Islands of Arctic Canada lie north of latitude 74° 30′ N several hundred miles from the Canadian mainland, and far inside the Arctic Circle. They are bounded, in the form of a triangle, on the south by the Parry Channel, on the east by the bays and sounds that run in a northeast direction off the west coast of Greenland, and on the northwest side by the Arctic Ocean (Fig 1).

The islands present a great variety of landscapes and geological formations which may be divided roughly into five main sections:

1. The Pre-Cambrian Shield in the eastern section extends northwards as a tapering zone through eastern Devon Island to an area about half way up the east coast of Ellesmere Island. This is marked by high ice-covered uplands, sometimes with bold and rugged coasts and elsewhere with spectacularly fjorded coastlines.

2. A plateau of gently dipping sedimentary rock lies across western Devon Island and the western half of southern Ellesmere Island.

3. A belt of folded sedimentary rocks runs from the western coast of Melville Island through the islands on the northern side of the Parry Channel as far east as Cornwallis Island, and thereupon curves northeast through Grinnell Peninsula and the greater part of Axel Heiberg Island, on through central Ellesmere Island in a northeasterly direction. The terrain in many parts of Ellesmere Island and Axel Heiberg Island is high and rugged, but in the south and west on Cornwallis and Bathurst Islands the heights decrease and the folds are more eroded and weathered, resulting in rolling topography.

4. North and west of this folded zone is the Arctic Coastal Plain, which includes Prince Patrick Island to the west, the northern parts of Melville and Bathurst Islands, and islands of the Sverdrup group. The coasts are low, flat, and usually featureless, particularly those which face towards the Arctic Ocean.

5. The northern extension of the sedimentary zone which forms the plateau on northwestern Banks Island and northeastern Victoria Islands is to be found north of the Parry Channel in the southern part of Melville Island.

Ellesmere Island, with an area of approximately 80,000 square miles, is the largest of the islands in the Group and probably the most varied, possessing mountains exceeding 9000 feet with spectacular glaciers in some parts and rolling plains and uplands in others. The other large islands are Devon, Melville, and Axel Heiberg, ranging from 21,000 to 13,000 square miles and having quite a diversity of character. However, as a contrast, the islands of the Arctic Coastal Plain are generally low and featureless, with shallow coastal waters, low shore-lines, and rolling hilly interiors a few hundred feet in height. The total

* MS received 4 November 1960.

† Lobitos Oilfields Canada Ltd.

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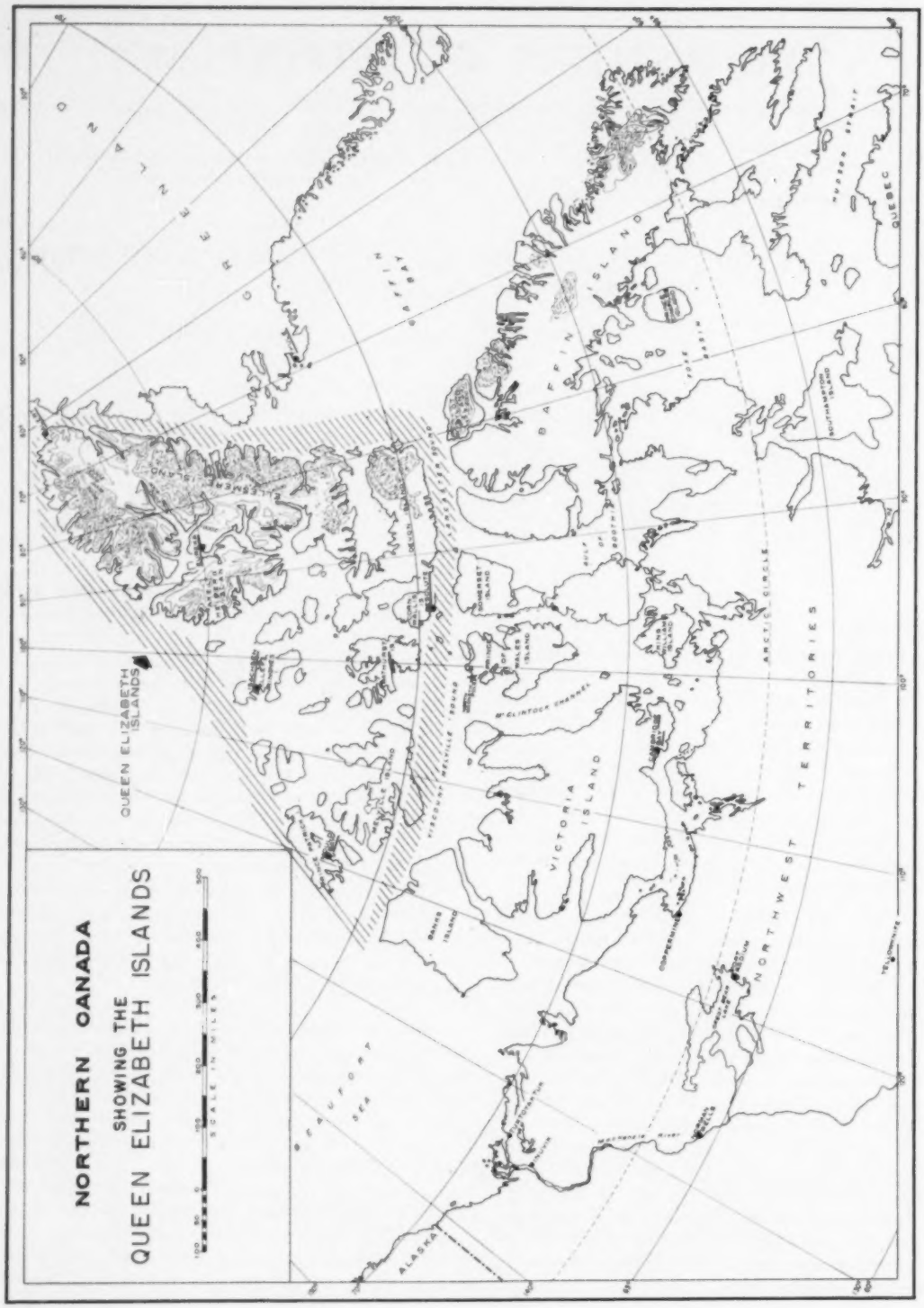

NORTHERN CANADA
SHOWING THE
QUEEN ELIZABETH ISLANDS
QUEEN ELIZABETH ISLANDS
BAFFIN ISLAND
VICTORIA ISLAND
NORTHWEST TERRITORIES
QUEBEC
ARCTIC CIRCLE
BEAUFORT SEA
ALASKA
BANKS ISLAND
SCALE IN MILES

Fig 1

area of the Queen Elizabeth Islands must exceed 150,000 square miles.

Population

There are about 10,000 Eskimos residing in the Canadian Arctic, but practically all of these inhabit regions south of the Queen Elizabeth Group. There are, however, about one hundred living in the vicinity of the RCAF Station at Resolute Bay, Cornwallis Island, and fewer on Ellesmere Island near the two Royal Canadian Mounted Police Posts. The Government is taking steps to provide training and employment for all Eskimos with the intention of enabling them to participate fully in the developments now rapidly occurring in these Arctic regions.

Also living in the islands are service personnel, Department of Transport communications and meteorological staff, together with government scientists, officers of the Department of Northern Affairs and National Resources, and detachments of the Royal Canadian Mounted Police. According to season, their numbers vary considerably, but can total some three hundred.

Transportation and Communications

Around August each year, during the open water season, ships from Montreal bring in several thousand tons of supplies to Resolute Bay. Aircraft are then used to carry the supplies to weather stations such as Isachsen and Mould Bay, and other areas of scientific activity. However, Eureka, a weather station half way up the west coast of Ellesmere Island, is regularly revictualled each year by sea.

Air transport is of considerable importance in all northern operations, and as a result all-weather landing strips are to be found not only at the RCAF Station at Resolute Bay, but also at the four other weather stations in the islands, and it is hoped that more will be built in the relatively near future. In the spring, ski-equipped planes are able to make use of frozen lakes and other stretches of level ice or snow as landing strips; hence this is the time for preparing caches of supplies in isolated spots for use in the subsequent summer.

There is a good network of radio communications at weather stations and air force sites, so contact within the islands and outside them too can be maintained.

Administration

The Queen Elizabeth Islands form part of the District of Franklin, one of the three districts forming the Northwest Territories. These Territories are administered by a Legislative Council over which the Deputy Minister of Northern Affairs and National Resources from Ottawa presides in his capacity as Commissioner. Five of the nine Councillors are appointed to the Council, while the other four are elected. This body is empowered to draw up ordinances and make recommendations for the welfare and good government of the area, one of the most important duties of the Council being the preparation of regulations aimed at protecting the Eskimos, who mainly depend for their living upon hunting and trapping.

Enforcement of the regulations of the Northwest Territories' Council is the responsibility of the Royal Canadian Mounted Police, who have various social welfare duties to perform as well. In addition, Northern Service Officers are posted to some settlements in the Northwest Territories to guide and assist the Eskimos generally. Schools have been built, and at certain centres boarding schools and vocational training courses are provided. The overall policy is to train all Eskimos so that they are able to take part fully in the vast and rapid developments that are occurring in the far north.

Petroleum regulation and administration are the responsibility of the Department of Northern Affairs and National Resources. The Chief of the Resources Division has his office and staff in Ottawa, while the Oil Conservation Officer for the Northwest Territories carries out his duties from the petroleum centre of Calgary.

Vegetation and Wild Life

While there are no trees or upright shrubs in the Queen Elizabeth Islands, one of the most surprising features of the landscape is the variety and relative wealth of plant life, which includes scrub willow, grasses, moss, and lichens. For a short, gay season bright coloured flowers are widespread.

There are two large Arctic herbivores, the musk-ox and the caribou. The former is found chiefly in the Queen Elizabeth Islands, with grass and leaves as its main food source. The caribou on the mainland to the south migrates in large herds, while in the islands they have been known to move from one island to another over considerable expanses of sea ice. They live chiefly on lichens. Large white arctic hare and the smaller mouse-like lemming are probably the most numerous of all the herbivorous species in the region. The hare is found in many rocky areas, but the lemming is much more widespread, although their numbers are strangely subject to cyclic increases and decreases roughly every four years. As the arctic fox, which is economically the most important of the animals of the Canadian Arctic, preys on lemmings, their population in any particular year and the quality of their pelts is dependent on the seasonal number of lemmings. Weasels and wolves also exist in the islands.

However, the most prolific source of life is not the land but the sea. Seals are to be found in all regions close by open leads in the ice and at breathing holes kept open by themselves throughout the winter. Then there is the powerful and amphibious polar

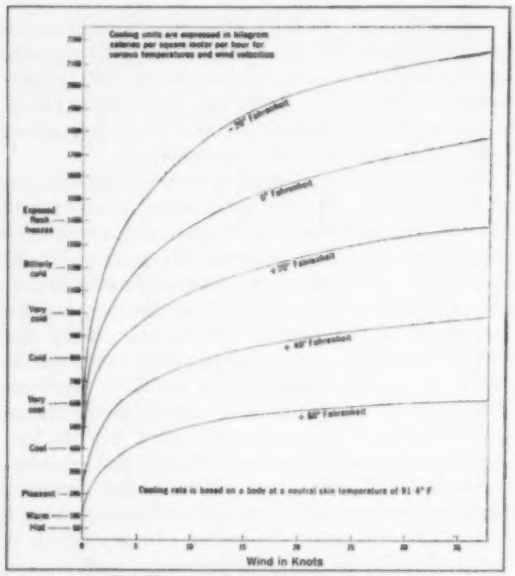
bear, which spends practically all its life on or beside the sea, pursuing seals with the greatest of cunning. The larger whales, hunted almost to extinction, are now slowly re-establishing themselves, but the most prolific to-day are the smaller species such as the narwhal, sometimes called the "sea-unicorn," and the white whale. The walrus, or "seahorse," is also found throughout the islands. Of the fish in the seas and rivers, probably the best known is the Arctic char, a fish very similar to the salmon.

Many species of birds, particularly water fowl, use the Arctic as their summer breeding grounds, and arrive in flocks from all latitudes of the American continent. During the summer, duck, geese, fulmars, jaegers, and other water and wading birds are numerous. Ptarmigan, hawks, gyrafalcons, ravens, and owls are also present, but as a rule only the owls, ravens, and some ptarmigan remain throughout the winter.

Mosquitos and black flies which are the well known summer curse of the Arctic mainland, most fortunately tend to disappear north of the Parry Channel.

Climatic Conditions

The highest recorded temperature at Resolute Bay is plus 61° F, with a monthly average daily maximum



Wind chill on exposed personnel in state of inactivity

FIG 2

of plus 46° F for July, while the lowest reading at the same station is minus 61° F, with an average daily minimum of minus 41° F for January. At Eureka, farther north, the summer temperatures surprisingly average 2° higher than at Resolute Bay, but in the winter they fall into line, averaging 5° less. Low temperatures, such as minus 40° F, are not uncommon in the areas on the Canadian mainland where drilling operations are currently conducted, but the big differences in the sub-arctic are the frequent reliefs from the extreme lows, the much shorter winter, and the fact that there is no season of darkness throughout the whole of a day.

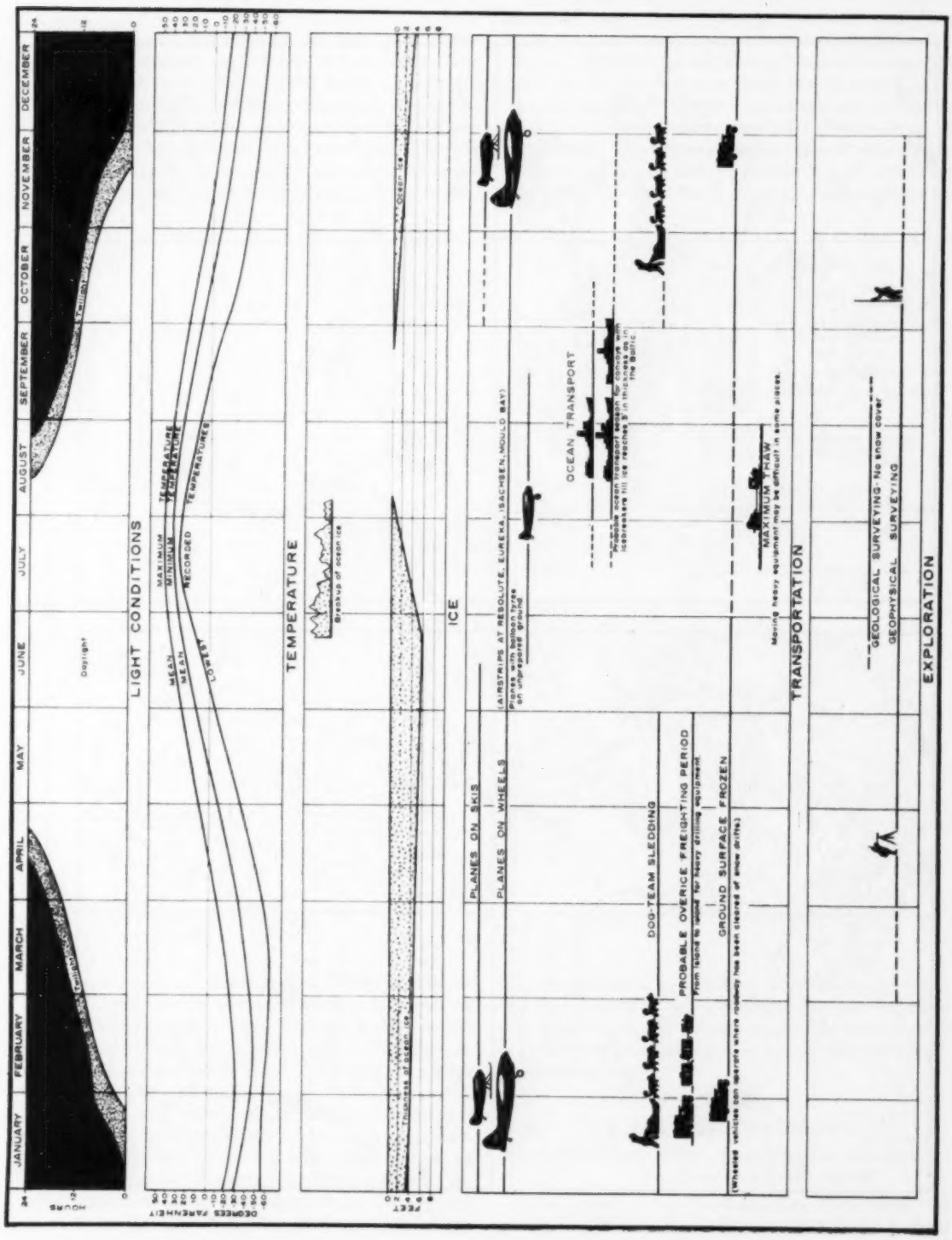
Moderate winds up to 40 mph are common, but they can reach 100 mph on occasions. The normal winds would not be troublesome in the summer, but when coupled with low temperature in the winter, a wind chill condition is created that considerably reduces the efficiency of crews unless most thorough winterization of all camps and equipment is carried out (Fig 2).

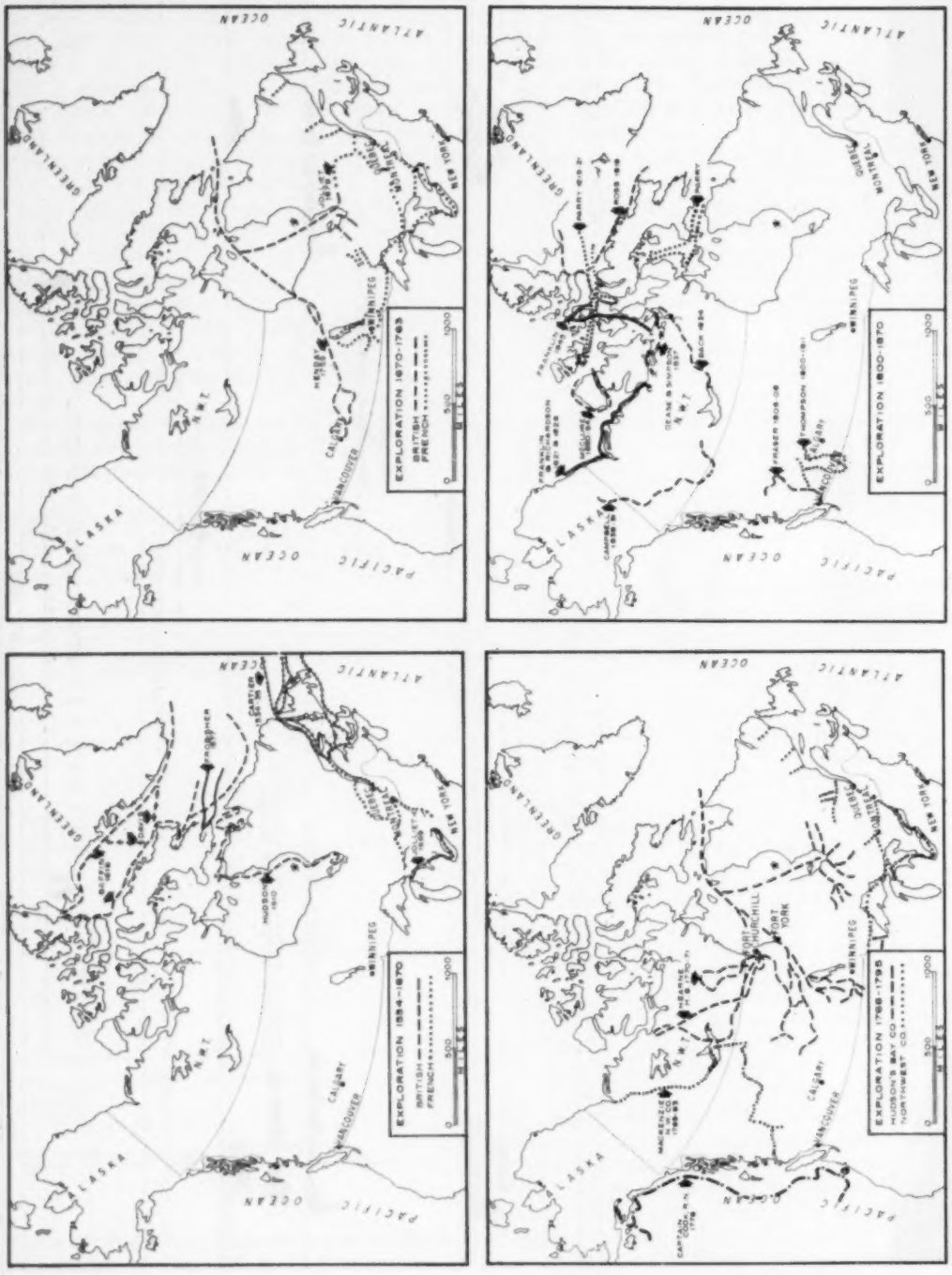
Precipitation is so very light that much of the area can be described as a frozen desert. During the summer three months all snow melts, except from hills and mountains about three thousand feet or more in height. The absence of snow cover is, of course, of the utmost importance in permitting aerial photographic studies and surface geological investigations of the prospective oil-bearing parts of the islands (Fig 3).

Exploration

While the French in southern Canada between 1534 and 1670 progressed up the St Lawrence River as far as Sault Ste Marie, the British navigators, Frobisher, Davis, Hudson, and Baffin, discovered the west coast of Greenland, the east coast of Baffin Island, and the large inland sea, Hudson Bay (Fig 4). During the hundred years following 1670, when the French extended their power as far west as Winnipeg, the British made great use of Hudson Bay and established such famous trading posts as Fort Churchill and Fort York on its southwestern shores. The next thirty years was a period of rivalry between the Hudson's Bay Company and the North West Company, with the area of conflict centred round Lake Winnipeg. During these years Mackenzie of the North West Company explored the Mackenzie River down to its mouth on the Arctic Ocean, and Hearne of the Hudson's Bay Company carried out lengthy journeys from Fort Churchill northwards in the Arctic. It was also during this period that Captain Cook sailed up the west coast of Canada as far north as Alaska.

However, as far as exploration of the Arctic Archipelago in general and the southern part of the Queen Elizabeth Islands in particular is concerned, the years between 1800 and 1870 were of great importance. The voyage of Ross in Davis Strait and Baffin Sea in 1818 was followed a year later by the magnificent journey of Parry through Lancaster Sound as far west as 113° W, off the south coast of Melville Island. In so doing he earned a £5000 bounty offered by the British Government to the first expedition to pass the 110th west meridian and Cape Bounty, the nearest


JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
LIGHT CONDITIONS
Daylight
TEMPERATURE
MEAN MAXIMUM TEMPERATURE
MEAN MINIMUM TEMPERATURE
LOWEST RECORDED TEMPERATURES
DEGREES FAHRENHEIT
Breakup of ocean ice
Ocean ice
FEET
ICE
PLANES ON SKIS
PLANES ON WHEELS
AIRSTRIPS AT RESOLUTE, EUREKA, SACHEN, MOULD BAY
DOG-TEAM SLEDDING
PROBABLE OVER-ICE FREIGHTING PERIOD
From ice-strengthened ships on unprepared ground
From ice-strengthened ships on ice reaches 3' in thickness on the Baltic
From ice-strengthened ships on ice reaches 6' in thickness on the Baltic
From ice-strengthened ships on ice reaches 9' in thickness on the Baltic
From ice-strengthened ships on ice reaches


ATLANTIC OCEAN
GREENLAND
NEW YORK
WINNIPEG
CALGARY
VANCOUVER
ALASKA
PACIFIC OCEAN
EXPLORATION 1670-1763
BRITISH
FRENCH
EXPLORATION 1800-1870
EXPLORATION 1854-1870
BRITISH
FRENCH
EXPLORATION 1768-1795
HUDSON'S BAY CO
NORTHWEST CO
CHURCHILL
FORT YORK
HUDSON
MACKENZIE
1789
1793
FRANKLIN
1819-22
1825-27
1829-33
1845-47
1848-49
1850-51
1850-54
1851-53
1852-54
1853-54
1857-59
1858-60
1860-61
1867-68
1869-70
1870
THOMPSON
1800-01
FRASER
1808
1824-25
DEASE & STRONG
1828
BACK
1833-34
1834
1836-37
1837-39
1839-40
1842-43
1844
1846-47
1847
1848
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1851
1852
1853
1854
1857
1858
1859
1860
1861
1867
1868
1869
1870
CAPTAIN COOK
1778
0
500
1000
STATUTE MILES

FIG 4

prominent cape to this goal, has been named in honour of this.

Franklin made his name in the early part of this period by his overland journey to Coppermine and then by boat eastwards, followed shortly afterwards by his trip to the mouth of the Mackenzie and subsequent explorations by two boat parties eastwards and westwards. About twenty-five years later Franklin was again back in the Arctic, this time commanding a British naval expedition to search once again for the Northwest Passage. His two ships *Erebus* and *Terror* sailed in 1845; by September 1846 they lay beset off the northwest coast of King William Island at the entrance to Victoria Strait, never again to be free. In April 1848, a year after Franklin's death, the ships were abandoned and the 105 survivors began a march southwards, but all perished. Relief expeditions were sent out from England in 1848, one by the overland route, another by Bering Strait, and a third by Lancaster Sound. These resulted in a period of intense exploration activity which led to the mapping of most of the islands in the southern part of the Queen Elizabeth Group.

Following the establishment of weather stations at Resolute Bay, Eureka, Mould, Isachsen, and Alert after the last war, yet another phase of exploration began. RCAF reconnaissance flights and trimetrogon photographic surveys completed the discovery of all new islands, while the Geological Survey of Canada have conducted extensive geological examinations on all of them. More recently aerial vertical photographs taken of the whole Group has enormously eased the search by the oil industry for structures suitable for the entrapment of petroleum. It would appear that this last period of exploration that has now begun in the Queen Elizabeth Islands might this time, and in the relatively near future, lead to considerable economic development.

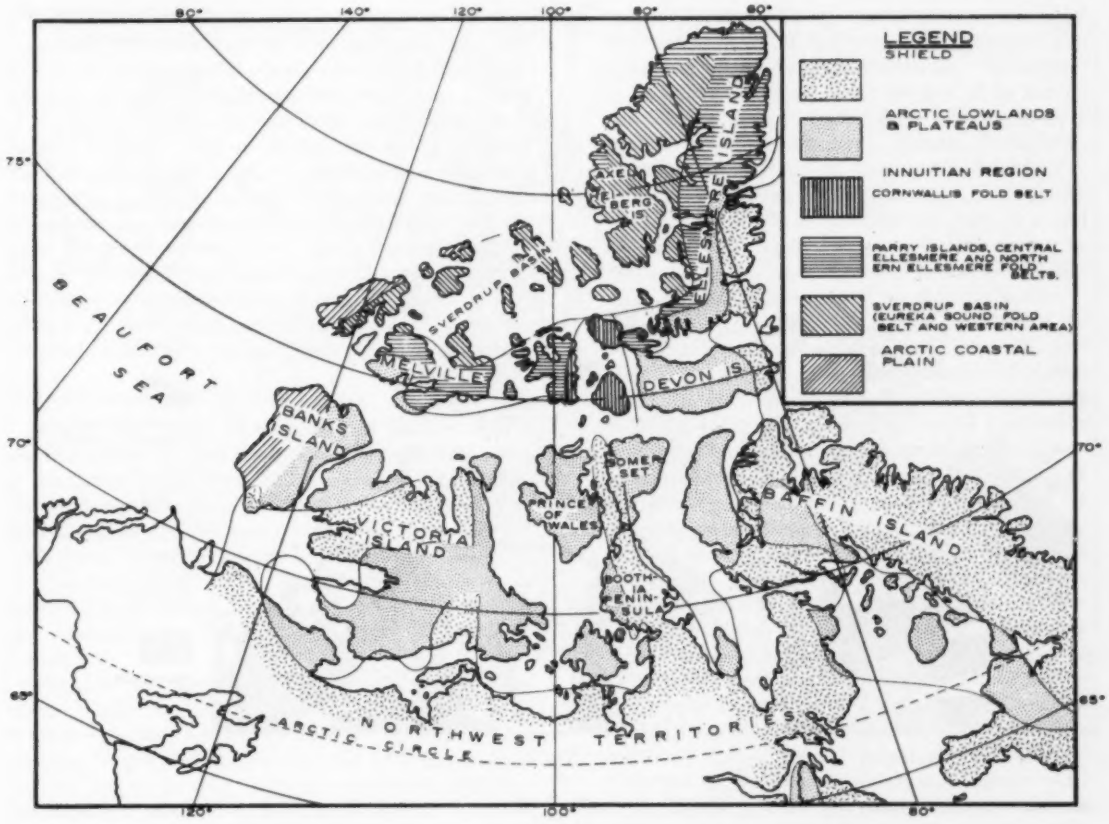


FIG 5

GEOLOGICAL CONDITIONS

Structural History of the Queen Elizabeth Islands since Pre-Cambrian Time

Subsequent to the Pre-Cambrian there were two periods of Palæozoic tectonism. The first of these occurred in late Silurian or early Devonian time and

produced north-trending structures on Cornwallis and eastern Bathurst Islands and maybe a part of Grinnell Peninsula—the Cornwallis Fold Belt (Fig 5). The second period in Upper Devonian time resulted in the formation of the Parry Island Fold Belt running from Melville Island to Bathurst Island, and from Grinnell Peninsula of Devon Island in a northeasterly direction to central and north Ellesmere Island. The folding in the Parry Island Belt involves a conformable Ordovician–Upper Devonian section, which in turn is overlain unconformably by marine Middle Pennsylvanian strata. It thus follows that the main Palæozoic orogeny of the Queen Elizabeth Islands is post-Upper Devonian pre-Middle Pennsylvanian.

The Ringnes and northwestern Queen Elizabeth Islands were the scene of downwarping in Permo-Carboniferous times and resulted in the Sverdrup Basin, which lasted well into Tertiary times. The basin axis extends from northern Sabine Peninsula of Melville Island to the Ringnes Islands, and hence across Axel Heiberg Island to the entrance to Greely Fjord in Ellesmere Island. This axis marks the site of heavy sedimentation from Pennsylvanian to Tertiary, but the synclinal limbs on Borden and Mackenzie King Islands to the west, northern Melville and Bathurst Islands to the south, and the lands in the vicinity of Norwegian Bay to the east have comparatively thin sections of rocks representing only part of this long time interval.

An orogeny occurred in Tertiary times which affected the Sverdrup Basin, causing Permo-Carboniferous evaporites deposited in the axial region to be thrust upwards as diapiric intrusions. In the Ringnes Islands and west Axel Heiberg Island the axis of the diapiric folds trend north to northwest transverse to the basinal axis. In the extreme eastern part of the basin, by Mokka Fjord of Axel Heiberg and Fosheim Peninsula of Ellesmere Islands, the folding and thrusting trend north to northeast, in places superimposed on the pre-existing Parry Islands folds. The western portion of the basin was little affected by this Tertiary orogeny.

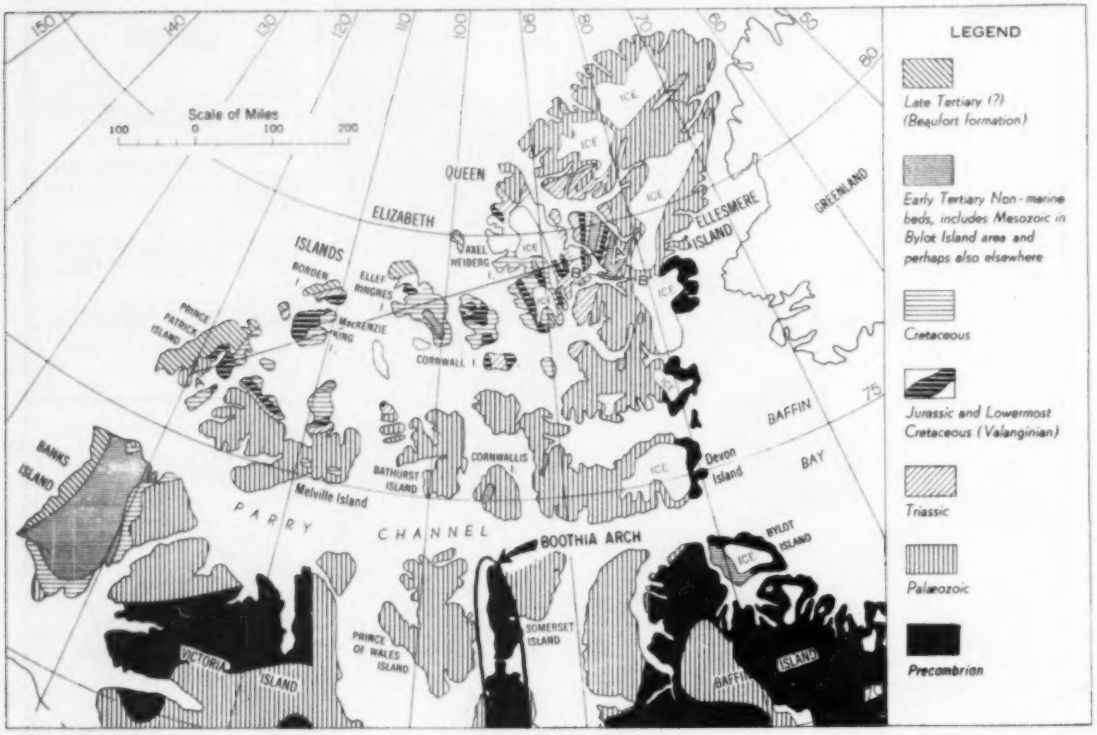


FIG 6

Palæozoic Stratigraphy of the Queen Elizabeth Islands (Fig 6)

(i) *Cambrian*

Cambrian rocks are found exposed at three places in the extreme eastern part of the Islands, but possibly they extend westward underneath younger rocks. At Dundas Harbour, in southeastern Devon Island, Lower Cambrian, resting unconformably on Pre-Cambrian gneisses and granite, consist of 100

feet of calcareous and glauconitic sandstone, overlain by more than 1000 feet of Middle Cambrian limestone emitting a petroliferous odour in its lower part along with minor thicknesses of sandstone and shale.

(ii) *Cambrian or Ordovician*

In the western part of Melville Island the Canrobert formation, consisting of silty dolomite and conglomerate, resembles the Cambrian and Lower Ordovician formations of eastern Devon Island.

(iii) *Lower Ordovician*

A Lower and Middle Ordovician section about 2000 feet thick at Dundas Harbour consists of limestone, dolomite, conglomerate breccia, and sandstone. Many of these beds emit a petroliferous odour when fractured. Farther west on Devon Island by Burnett Inlet more than 1000 feet of limestone and dolomitic limestone, probably Lower Ordovician, lies unconformably over Pre-Cambrian gneiss, while much the same thing is to be seen on the north coast of the same island. Rocks lithologically similar to those just mentioned are also present on southern Ellesmere Island, while on the east coast of Ellesmere Lower Ordovician limestone and limestone conglomerate are to be found.

(iv) *Ordovician and Silurian*

Middle and Upper Ordovician and Silurian strata are widespread in the region of folded Palæozoic rocks of the Parry Island Fold Belt, and are to be found in the lowlands and plateaux to the south as well. It would appear that in many regions in the south the beds were laid down directly on the Pre-Cambrian by shallow transgressive seas, but as already stated, in eastern Devon Island these beds are separated from the basement by Cambrian and older Ordovician formations.

Strata of the ages under discussion include widespread shelly faunæ, amongst them being the well-known "Arctic Ordovician Fauna" of Middle and possibly Upper Ordovician age, and also the characteristic fauna in the Silurian—*Atrypella Scheii*—which ranges in age from Middle to Upper.

South of the Queen Elizabeth Islands the Ordovician and Silurian strata have a shelly faunæ and are mainly carbonate rocks. Much the same applies to some of the Ordovician and Silurian formations in both the Cornwallis and Parry Islands fold belts, except that, within the main part of the belt itself, shelly strata do change partly or entirely to a graptolitic series, a change that appears to have been initiated in Lower Ordovician time in the western part of the Parry Islands Belt and in late Middle Ordovician time in the Cornwallis Belt. These graptolite formations, whose fauna occur not only in impure carbonate rocks and shales but also in sandy Upper Silurian strata, range well into the Silurian and are in part correlative with the shelly Silurian formations.

On Cornwallis Island the following formations make up Middle and Upper Ordovician and Silurian rocks:

(a) *The Cornwallis Formation*, of Middle Ordovician age, is in sharp contact with the overlying Allen Bay formation. There are several thousand feet of varied but predominantly carbonate strata. The basal 800 feet consist of siltstone and shale, alternating with strata of limestone, gypsum or anhydrite, and gypsiferous shale. The widespread evaporite sequence in its lower part is noteworthy. These strata are overlain by alternating beds of limestone and impure limestone and a few interbeds of siltstone. The uppermost strata comprise about 60 feet of limestone overlain by 20 to 40 feet of shale which contain a prolific representation of "Arctic Ordovician Fauna." As well as on Cornwallis Island, the formation outcrops on the east coast of Bathurst Island, extensively on the Grinnell Peninsula and elsewhere on Devon Island, and also occurs at wide-spread localities in central Ellesmere Island. A significant outcrop exists on Melville Island.

(b) *The Allen Bay*, of Middle Ordovician to Middle Silurian age, overlies the Cornwallis formation on southern Cornwallis Island. It is 5000 feet thick and consists mainly of dense to porous dolomite. It further occurs above the Cornwallis in the southern and eastern parts of central Ellesmere belt and the Druro Range, amounting in one locality to 3700 feet mainly of dolomite. It also outcrops along a large tract of westerly dipping land on western Devon Island, and on a number of islands lying south of the Queen Elizabeth Group.

(c) *The Read Bay*, overlying the Allen Bay formation conformably in the southern part of Cornwallis Island and grading into it, is of Middle and Upper Silurian age. Its aggregate thickness of 8425 feet has been sub-divided into four members consisting of Argillaceous limestone 1800 feet thick with a gradational contact with the underlying Allen Bay dolomite; shale about 100 feet thick; 4725 feet of strata lithologically similar to the first member; and finally a gradational passage into mainly calcareous sandstone beds 1800 feet thick. The Read Bay extends to parts of the Arctic lowlands and plateaux adjacent to the Cornwallis belt, while beds containing its typical *Atrypella* are widespread in the southern and eastern parts of the central Ellesmere Island.

(d) *The Cape Phillips* on northern Cornwallis Island lies conformably above the Cornwallis formation, and is Middle Ordovician to Upper Silurian in age. It represents a graptolitic facies that is correlative with the Allen Bay and most of the Read Bay shelly formations and comprises

8500 feet of impure carbonate rocks, shales, and cherty carbonates. The upper part of the formation is beneath an unconformable contact with the overlying Disappointment Bay formation of either Upper Silurian or Lower Devonian age. In the Parry Islands Fold Belt of central Bathurst Island it is thinner, being only 1700 feet thick and consisting of calcareous shales, shales, mudstones, and argillaceous limestones, silty in the upper part. On the west coast of Melville Island 3500 feet of Lower Ordovician to Upper Silurian, Ibbett Bayblack shale, and argillitic graptolitic strata are exposed. However, while graptolitic, these beds, stratigraphically, do not reach as high as the Cape Phillips, but are correlative with the Cornwallis and older formations. Finally, it should be noted that in the central Ellesmere Fold Belt graptolitic strata that do appear correlatable with the Cape Phillips are exposed and overlie Cornwallis formations or probable Cornwallis formations.

(v) *Silurian and Devonian*

On the east coast of Cornwallis Island the Snowblind Bay formation, either Upper Silurian or Lower Devonian, conformably overlies and grades into the Read Bay formation. It is made up of 800 feet of limestone breccia, limestone conglomerate, red sandstone, and siltstone. Further north the Disappointment Bay formation, consisting of at least 280 feet of dolomite, sandstone, and limestone conglomerate, overlies the Cape Phillips with angular unconformity; it is also Upper Silurian or Lower Devonian.

On the central part of the east coast of Bathurst Island, still in the Cornwallis Fold Belt, the Cape Phillips formation is overlain conformably by the Middle Silurian Sherard Osborne formation, which consists of dolomite reefs, limestone, and sandstone. In west Bathurst Island the Cape Phillips graptolitic formation is covered by the Bathurst formation, some 3400 feet of argillaceous and calcareous siltstone, sandstone, and limestone, which becomes sandier as the overlying Stuart Bay formation, 1200 feet thick, is approached. The Bathurst formation may be classed as Upper Silurian, and the Stuart Bay Lower Devonian. More strata of Upper Silurian or Lower Devonian age are to be found in northwest Devon, and southwest Ellesmere Islands, while farther north in central Ellesmere Pre-Pennsylvanian and younger than Silurian graptolitic shale beds outcrop.

(vi) *Devonian Rocks*

Eastern Bathurst Island, lying in the Cornwallis Fold Belt, was a positive area from Upper Silurian to Middle Devonian times. However, rocks ranging in age from Lower to Upper Devonian are to be found extensively in the Parry Islands Fold Belt of the western two-thirds of Bathurst Island, where there was continuous sedimentation within that time interval. Because of the regional plunge to the west together with normal erosion, the older formations are found exposed mainly on the eastern parts of the Parry Island anticlinal folds. The Devonian succession on Bathurst Island is as follows:

(*a*) The Lower Devonian Eids formation of black calcareous shales 1050 feet in thickness conformably overlies the Stuart Bay.

(*b*) The Blue Fjord formation of light crystalline limestone, accompanied by shale and mudstones, ranges from 2500 feet in thickness up to 3500 feet. It is noteworthy that south of the Variscan Anticline a marked facies change to bioclastic crinoidal limestone occurs in its lower part.

(*c*) The Bird Fjord formation overlies the Blue Fjord conformably, and consists of limestone, sandy limestone, calcareous sandstone, and shales. It varies in thickness from 800 to 2100 feet, and becomes sandier up the section.

(*d*) The Okse Bay formation, 3000 to 4000 feet thick, is Upper Devonian and represents the first major deposition of continental sands within the Parry Island Fold Belt. It is subdivided into a lower tan porous sandstone, a middle soft white sandstone, and an upper dark shale and siltstone member.

The Devonian succession on eastern Bathurst Island in the Cornwallis Island Fold Belt is different. During Upper Silurian and Lower Devonian uplifting folding and erosion occurred. As a result, the Middle Devonian Driftwood Bay formation, consisting of 400 feet of sandstone and siltstone, rests with angular unconformity on the previously mentioned Middle Silurian Sherard Osborne. The succeeding Devonian section is thereafter similar to that found to the west with Blue Fjord, Bird Fjord, and Okse Bay overlying each other in ascending order.

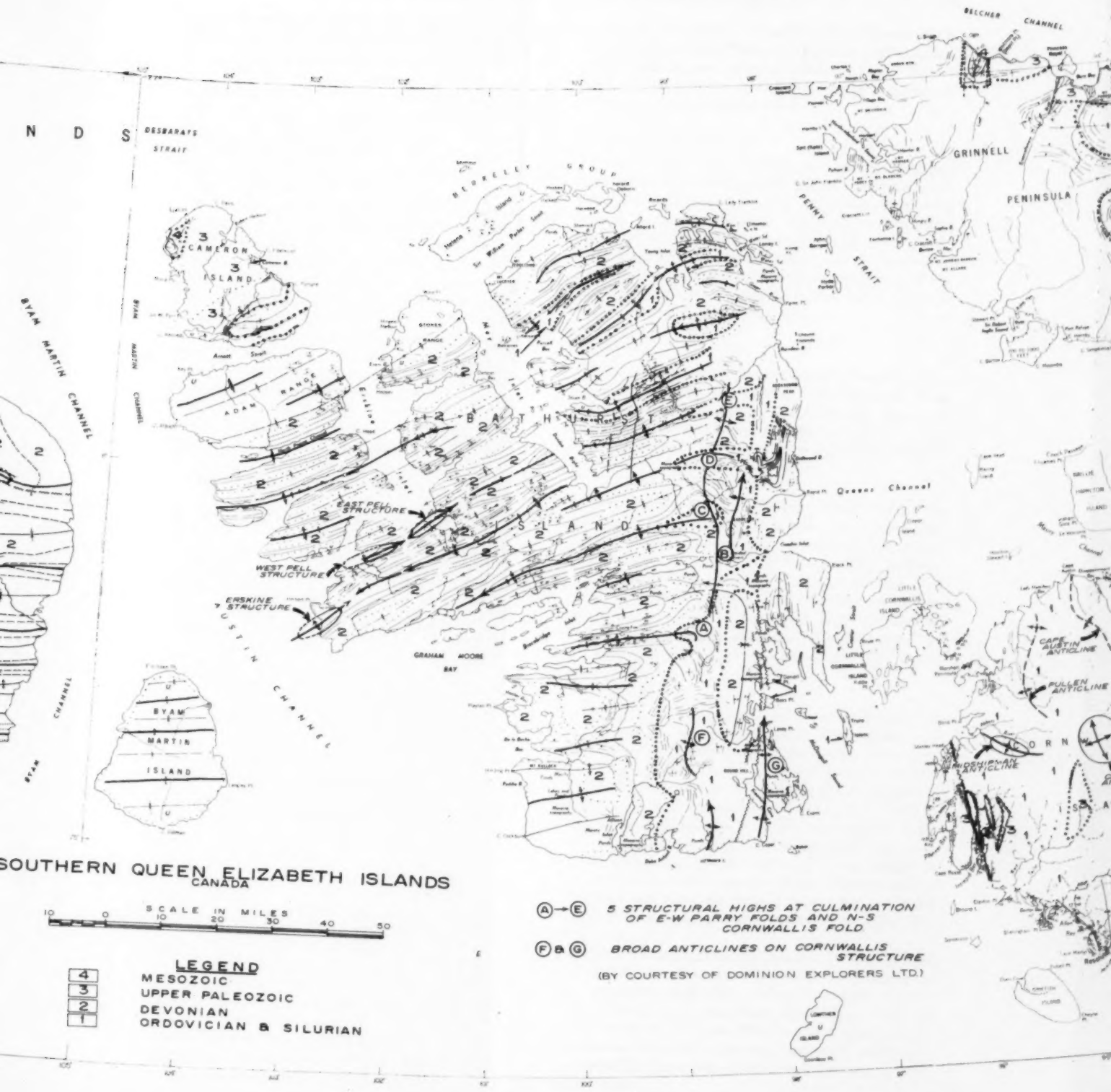
The exposed rocks of the Parry Island Fold Belt of eastern Melville Island are probably correlative with the Middle and Upper Bird Fjord and Okse Bay formation of western Bathurst Island. On western Melville Island, the Melville Island formation lies conformably over the Ibbett Bay graptolitic formation and is at least 11,000 feet thick. In this western region it consists principally of marine and non-marine sandstone, with shale, siltstone, and coal, and ranges in age from Middle to Upper Devonian. More of the Melville Island formation is exposed on Prince Patrick Island to the west, and there are also widespread Devonian strata in the central Ellesmere Fold Belt to the northeast.

(vii) *Permo-Carboniferous*

Permo-Carboniferous strata occur along the southern, eastern, and northern periphery of the Sverdrup

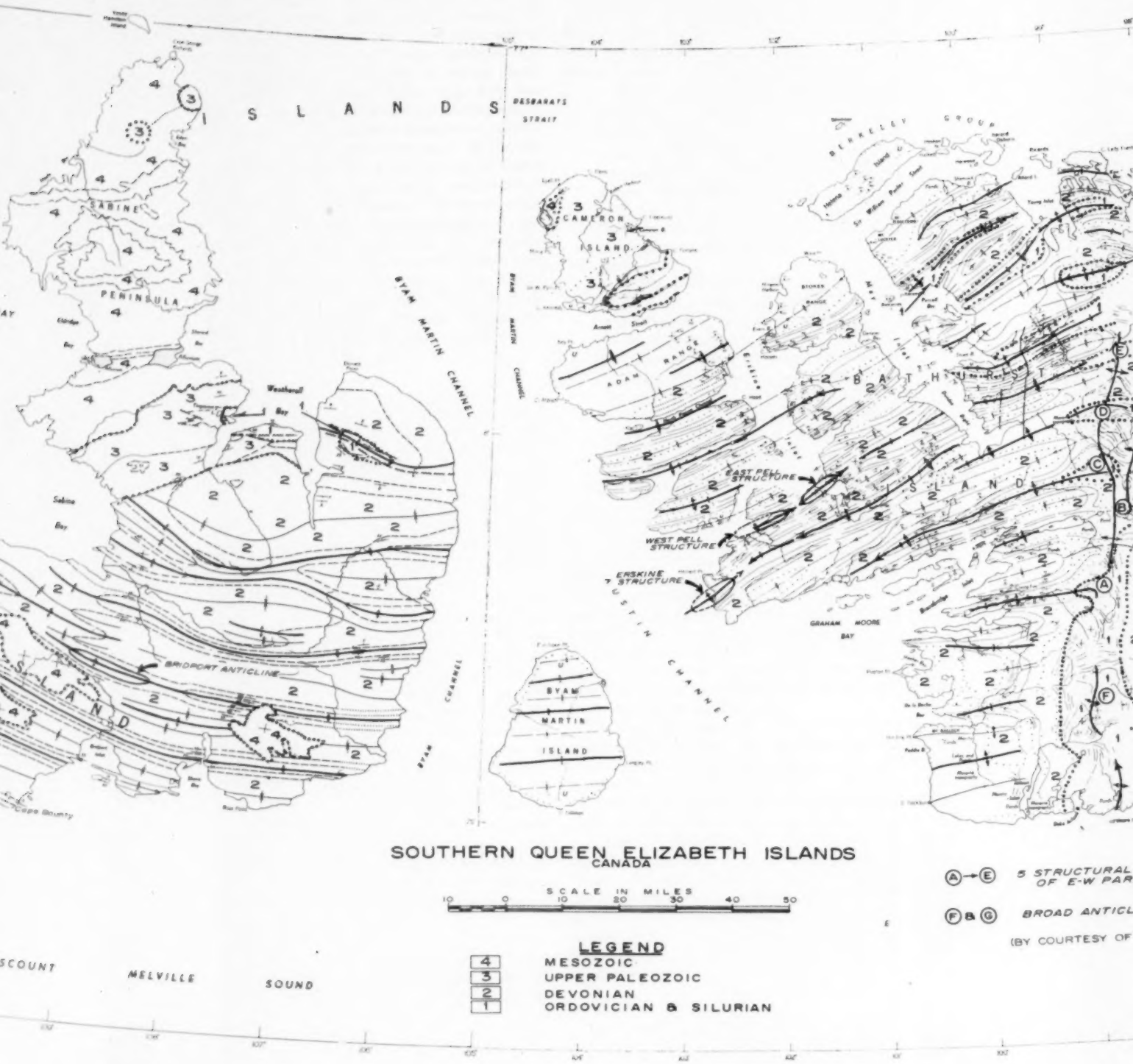
NORWEGIAN
NORTH DEVON ISLAND
COLIN ARCHIPELAGO
PENINSULA
BRIDPORT ANTICLINE
CAPE MOTHAM ANTICLINE
RESOLUTE BAY ANTICLINE
MELVILLE

PARRY
ISLAN
SABINE
PENINSULA
HECLA AND GRIPER BAY
HILLS
Liddon Gulf
BRIDPORT ANTICLINE
ISLAND
DUNDAS PENINSULA
Cape Bounty
VISCOUNT MELVILLE SOUND



SOUTHERN QUEEN ELIZABETH ISLANDS
CANADA

FIG 7



SOUTHERN QUEEN ELIZABETH ISLANDS
CANADA

Fig 7

AL HIGHS AT CULMINATION
ARRY FOLDS AND N-S
CORNWALLIS FOLD

CLINES ON CORNWALLIS
STRUCTURE

OF DOMINION EXPLORERS LTD.)

Basin, lying unconformably upon Upper Devonian and older strata, and are also to be found exposed within the cores of piercement domes and diapir folds of this Basin. In the central Ellesmere Fold Belt, units of limestone, sandstone with layers of conglomerate, and lesser units of shale generally occur together, but limestone is the most widespread type. However, on north Melville Island in the western part of the Parry Island Fold Belt, vividly coloured sandstone occurs almost to the exclusion of limestone.

Evaporites, mainly gypsum, form the cores of the piercement domes and diapir folds extending from the Sabine Peninsula through the Ringnes and western Axel Heiberg Islands northwards to Ellesmere Island. Blocks of limestone within the evaporites contain Permo-Carboniferous fossils, and it is thus probable that the evaporites are of this age or older. It is noteworthy that these evaporites have been intruded into much younger rocks, and their injection was accompanied by deformation of strata of Triassic, Jurassic, Cretaceous, and possible Tertiary ages.

Finally, at widespread localities in west central Ellesmere Island in the Eureka Sound Fold Belt extensive exposures of Pennsylvanian and Permian beds are present, lying with large angular unconformities over Ordovician, Silurian, and possibly younger beds.

Mesozoic and Tertiary Stratigraphy of the Queen Elizabeth Islands

The Mesozoic and Tertiary rocks of the Queen Elizabeth Islands are best developed in the Sverdrup Basin, the large sedimentary basin centred on Axel Heiberg and the Ringnes Islands, and consist of an essentially conformable Pennsylvanian to early Tertiary sequence. On the margins of the basin many formations show transgressive overstep with sections that are incomplete compared with those of the axis. Marine and non-marine formations alternate in the Mesozoic, but Tertiary beds are entirely non-marine and consist mainly of sandstone, shale, and coal—the Eureka Sound formation.

Within the Sverdrup Basin, Triassic formations reach a thickness of 17,500 feet; Jurassic 1500 feet; Cretaceous 12,000 feet; and Tertiary about 10,000 feet, but, as mentioned above, sections on the margins of the Basin are much thinner.

(i) *Triassic*

Known Triassic outcrops are limited to the Sverdrup Basin and particularly to the Eureka Sound Belt, where exposures are abundant and strata are thick. The Blaa Mountain formation of Middle, Upper, and probable Lower Triassic age occurs on west central Ellesmere for many miles, and is also found on eastern parts of Axel Heiberg Island. Here the formation consists of 4000 feet of siltstone with lesser shale overlain by 10,000 feet mainly of shale with siltstone.

In the western part of the basin fewer occurrences of Triassic are known. However, on northwest Bathurst Island an Upper Triassic limestone and an underlying calcareous sandstone of Middle or Upper Triassic age are at least 60 feet thick and in apparent structural conformity with Permian beds.

(ii) *Triassic and Jurassic*

A sandy formation, widespread in the Sverdrup Basin, is marine and Upper Triassic in its lower part, and is non-marine and possibly ranges into the Lower Jurassic in its upper part. On southeastern Axel Heiberg Island this sandy formation is 5600 feet thick, with sandstone, shale, siltstone, and carbonaceous material in the upper part. Other exposures of the sandy formation are present at Mokka Fjord, and also on Bjorne and Fosheim Peninsulas.

(iii) *Jurassic*

The Jurassic section is predominantly shale and is much thinner than the Triassic. Nevertheless, beds of Jurassic age extend from Prince Patrick Island on the west all the way around the periphery of the Sverdrup Basin to Fosheim Peninsula in the northeast.

(iv) *Jurassic and Cretaceous*

The Deer Bay formation of late Jurassic and early Cretaceous age is mainly shale with minor sandstone and siltstone. It ranges in thickness from 600 feet at Ellef Ringnes Island to 2500 feet at Axel Heiberg. On Fosheim Peninsula about 500 feet of shale and clay may possibly belong to the Deer Bay formation, while the lower part of the Mould Bay formation of Prince Patrick Island contains beds that may be correlative with the Deer Bay formation.

(v) *Cretaceous*

During this period there was an alternation of marine and non-marine deposition, while minor volcanic activity also occurred. The Lower Cretaceous Isachsen formation conformably overlies the Deer Bay formation and is widely exposed on the Ringnes and western Axel Heiberg Islands. Varying from 2000 to 4000 feet in thickness, it is mainly non-marine sandstone with shale, siltstone, and lithified wood. In most parts it is conformably overlain by the Lower Cretaceous Christopher formation, composed of shales and minor sandstone and siltstone ranging from 1500 feet thick on the Ringnes Islands up to 3000 feet on Axel Heiberg Islands.

Cretaceous basalt flows 600 feet thick occur on Axel Heiberg Island. These flows have 750 feet of conformable sandstone and shale below and 1200 feet of Middle Upper Cretaceous shale above them. On top of this shale are at least 8000 feet of a conformable sequence of siltstone, sandstone, and silty shale, with coal possibly extending from Upper Cretaceous into the Miocene.

(vi) *Tertiary*

Non-marine sandstones and shales commonly with lignite are deposited widely on Fosheim Peninsula and other parts of the northeastern Queen Elizabeth Group. They belong to the Eureka Sound Fold Belt and include possibly 7000 feet of folded sandstone, shale with Palæocene or Eocene plants, and lignite. This Eureka Sound Tertiary Group progressively oversteps the conformable Upper Palæozoic–Mesozoic section, next the belt of Palæozoic rocks folded before Middle Pennsylvanian times, and thirdly, Lower Palæozoic rocks unaffected by any Palæozoic orogeny. Further structural deformation took place in Tertiary times after the deposition of this Eureka Sound Group.

STRUCTURES WITH PETROLEUM PROSPECTS

General

The first structural map (Fig 7) shows that the Palæozoic folds on Cornwallis Island and the eastern part of Bathurst Island run in a northerly direction—the Cornwallis Fold Belt—while folds on the western part of Bathurst and on Melville Islands run in a direction that is more or less east and west—the Parry Island Fold Belt. These two fold belts join together on the eastern side of Bathurst Island. A second map indicates that in east Axel Heiberg and west central Ellesmere Islands a Mesozoic Tertiary anticlinal system runs north–south and has been named the Eureka Sound Fold Belt.

Structures on Cornwallis Island

The biggest structure on Cornwallis Island, the Centre Dome, is about seven miles in diameter and has closure amounting to several thousand feet (Figs 8–9). The rocks exposed on most of the periphery of the dome belong to the middle part of the Cornwallis formation (Middle Ordovician), but the basal evaporitic part is exposed in the very crest. Aerial magnetometer data suggest that there may be 10,000 feet of sediments underlying the crestal area, which is encouraging, but unfortunately no data are available to indicate the age or lithology of the underlying formations. Strata immediately overlying the Pre-Cambrian on two islands immediately to the south of Cornwallis have been examined, but no Cambrian rock was discovered. In fact, the nearest Cambrian exposures are those at Dundas Harbour on east Devon Island, and these have signs of being petroliferous, but as there is an area in between, at Burnett Inlet, where Ordovician rocks lie immediately on top of the Cambrian, it is difficult to postulate that Cambrian rocks will be present beneath the Centre Dome of Cornwallis Island.

The other structures on Cornwallis tend to be elongated in a north–south direction except for the Midshipman anticline, which trends roughly northwest–southeast. These structures can be seen on the map.

Structures on Bathurst Island

On the east coast of Bathurst Island are two anticlines, the Freeman's Cove and Dyke Bay structures, both running in a north–south direction and part of

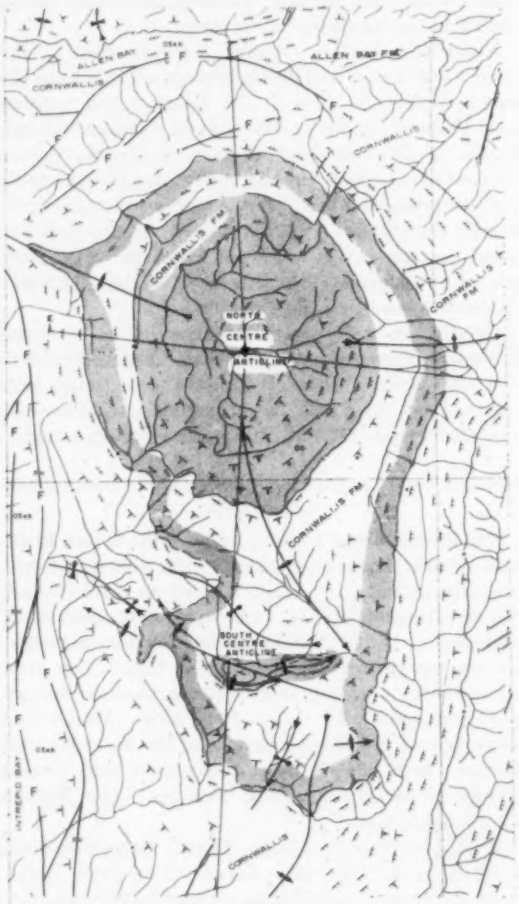


FIG 8

the Cornwallis Fold Belt. These structures have the equivalent of the Cape Phillips graptolitic shale in their crests, and thus the Cornwallis formation is the prospective horizon.

Just to the west of this line of north to south folding is a broad north to south Cornwallis Fold Belt arch which meets and crosses the east to west Parry Island

anticlinal folds. This results in five structures, all with considerable closure, running in a north–south direction being located at the junction of the north–south arch with five of the anticlinal folds. The Cape Phillips formation is again exposed on the structural highs, so once more the top of the Cornwallis formation would be the objective.

CENTRE DOME, CORNWALLIS ISLAND
7 MILES IN DIAMETER

FIG 9

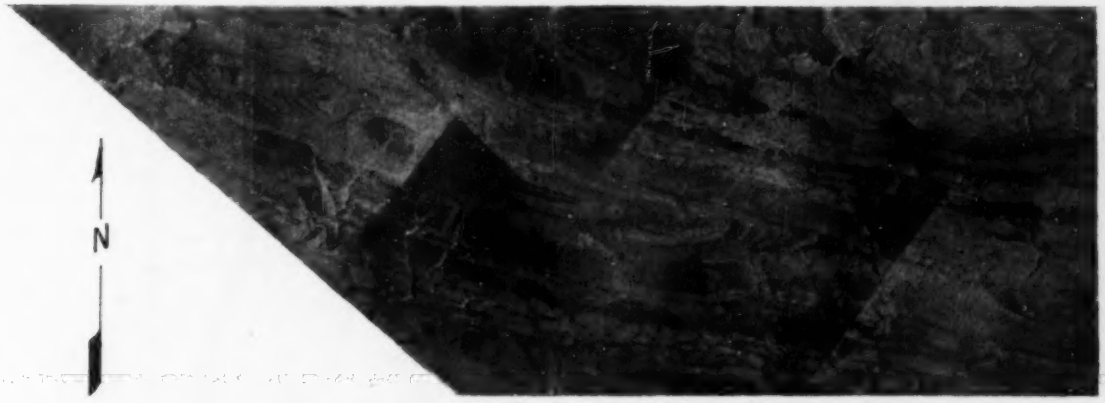
To the west of these five closed structures are twelve anticlinal folds of the Parry Islands Fold Belt, running in an ENE–WSW direction. They are all many miles in length, and all about ten miles apart. The folding appears to become more gentle towards the south, but general plunge of all the anticlines is towards the west, and hence there are younger rock exposures in that part of the island. Because of the regional plunge, these long structures are not generally closed. The only closure so far known is where there is a reversal of the westerly plunge, resulting in relatively minor closed areas.

Structures on Melville Island

Anticlines many miles in length are also to be found on Melville Island. These, like those on Bathurst Island, are about ten miles apart, running in an east–west direction. These folds become more gentle to the south and eventually die out.

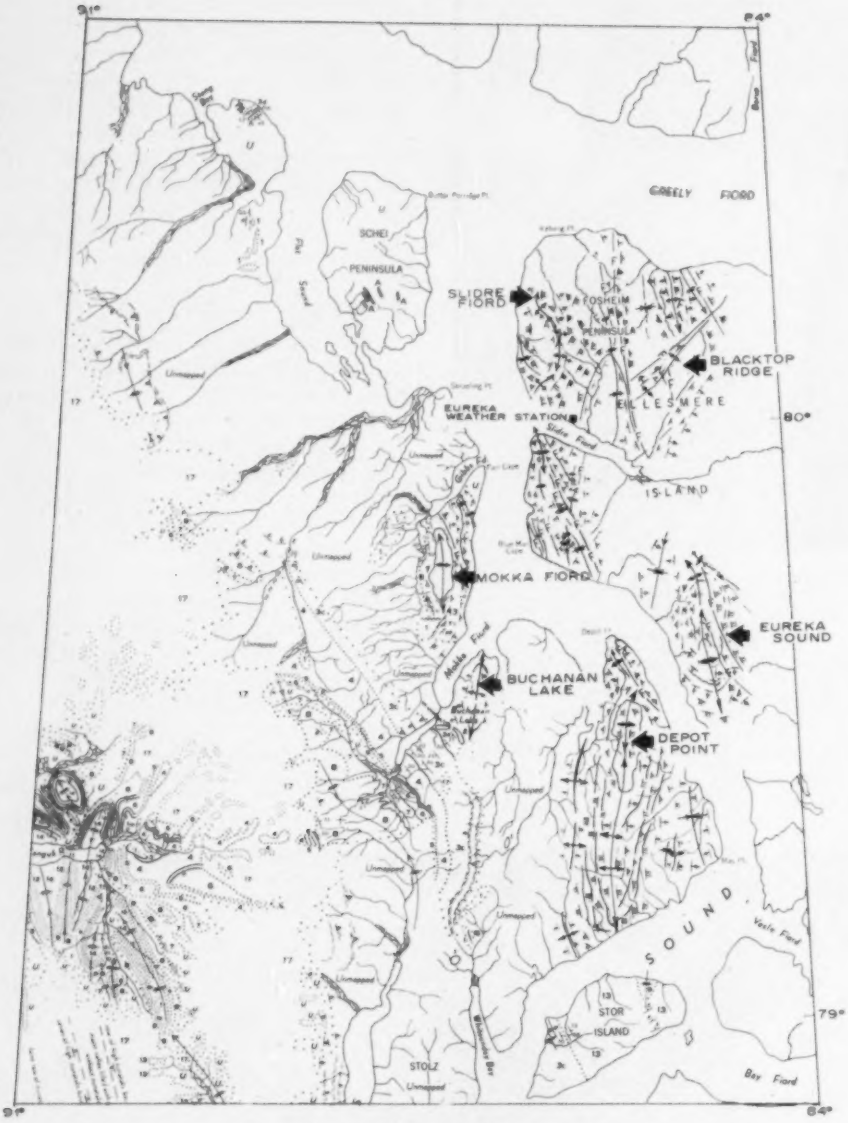
One of the biggest structures so far recognized is the Bridport structure situated immediately north of the Bridport Inlet on a rolling plateau. This shows up most clearly in aerial photographs (Fig 10). It is about two and a half miles wide and 18 miles long from its eastern to its western saddle.

A small normal fault runs along the northern flank of the structure parallel to the strike, but it is not considered to be of major significance. At the crest an exposed Devonian formation that might be correlated with limestone, sandy limestone, and shale of the Bird Fjord formation (Middle Devonian) of Bathurst Island has been named the lowest Melville Island formation.



BRIDPORT ANTICLINE, MELVILLE ISLAND

FIG 10



EUREKA SOUND,
FOSHEIM PENINSULA,
&
MOKKA FIORD AREAS
ARCTIC CANADA

SCALE IN MILES
0 10 20 30 40 50

FIG 11

FIG 12

Fig 13

Fig 14

Aerial photographs indicate the presence of other closed structures on the island, but these have not been examined in detail, so it is not possible to offer any comments.

Structures on Ellesmere and Axel Heiberg Islands

Six closed structures belonging to the Eureka Fold Belt have been discovered within 30 miles of the weather station at Eureka (Figs 11–15). Three of these structures lie on Fosheim Peninsula of western Ellesmere Island, while the other three lie across Eureka Sound in the Mokka Fjord area on the east coast of Axel Heiberg Island.

In the neighbourhood, overlying the older Palæozoics of the south, are structurally conformable sequences of Permian, Triassic, Jurassic, Lower Cretaceous, Upper Cretaceous, and Tertiary rocks totalling more than 20,000 feet, with sandstones and shales predominant. These structures are large and well-

folded and have good closure. In fact, there are abundant shale source rocks, ample thickness of sand and limestone reservoir rocks, and structural conditions suitable for the entrapment of petroleum.

Sverdrup Basin Structures

Salt domes occur along the axis of the Sverdrup Basin from the northern tip of Melville Island at the southwest to as far north as the northwestern part of Axel Heiberg Island. Two very striking domes are

FIG 15

found at the northern tip of Sabine Peninsula on Melville Island. At the other extremity are about 40 salt domes occurring at scattered points in the coastal areas of Axel Heiberg Island. Located in between these limits are four piercement dome type structures on Ellef Ringnes Island, and one large similar feature on Amund Ringnes Island. These have areas ranging from some 40 to 250 square miles.

Towards the south of Ellef Ringnes Island is the Hoodoo River structure, approximately 20 miles long and seven miles wide with relatively gentle dips, the maximum being 20 degrees (Fig 16). A small plug of Permian gypsum and anhydrite is to be found in the northwest part of the structure, which in turn is surrounded in a concentric fashion by Lower and Upper Cretaceous beds. Being on the axis of the Sverdrup Basin, about 50,000 feet of sedimentation can be expected.

SIGNS OF PETROLEUM

General

No oil or gas seeps have been discovered in the Queen Elizabeth Islands, but the signs of petroleum that have been reported in literature and the evidence obtained from geological surveys of the last two seasons show without doubt that the sedimentary rocks of the Queen Elizabeth Islands do provide an oil habitat. The absence of seeps may be attributable to the existence of more than 1000 feet of perma-frost.

Historical Review

(i) After wintering at Melville Island in 1819–20, Parry comments in his Journal on the naphtha odour of the rocks breaking under cartwheels when he crossed the island.

> "On the north side of this ravine large masses of sandstone were lying on the surface of the ground, over which the cart would with difficulty be dragged; and we remarked on this and several other occasions, that the stones which were bruised by the wheels emitted a strong smell, like that of fetid limestone when broken, though we could never discover any of that substance."

(ii) Belcher, in 1855, gave the name "Pitch Mount" to a hill on Grinnell Peninsula because of "a very strong naphtha and asphalt effluvium added to its swinestone (bituminous carbonate rock or anthraconite) formation."

(iii) McMillan, in 1910, found a limestone on Brown Island which "when broken emits a fetid odour resembling that of crude petroleum."

(iv) Ells, in 1909, commented that among the specimens collected by the Bernier Expedition on the beach of Melville Island were some rich black oil shales which kindled very rapidly into flame when ignited by a match.

(v) Bernier, in 1912, found bituminous shale from Hotspur Point, Bathurst Island, which on distillation gave crude oil.

(vi) Stefansson, in 1921, reports that a sort of pitch found west of the tip of Cape Grassy on the north coast of Melville Island burnt with a flame like that of sealing wax, and with an odour resembling that of asphalt. The pitch was used for kindling and as chewing-gum.

(vii) The widespread Allen Bay formation on Cornwallis Island contains massive dolomite beds, and these are generally porous, smell of petroleum, and in many places are charged with solid bitumen. A

T

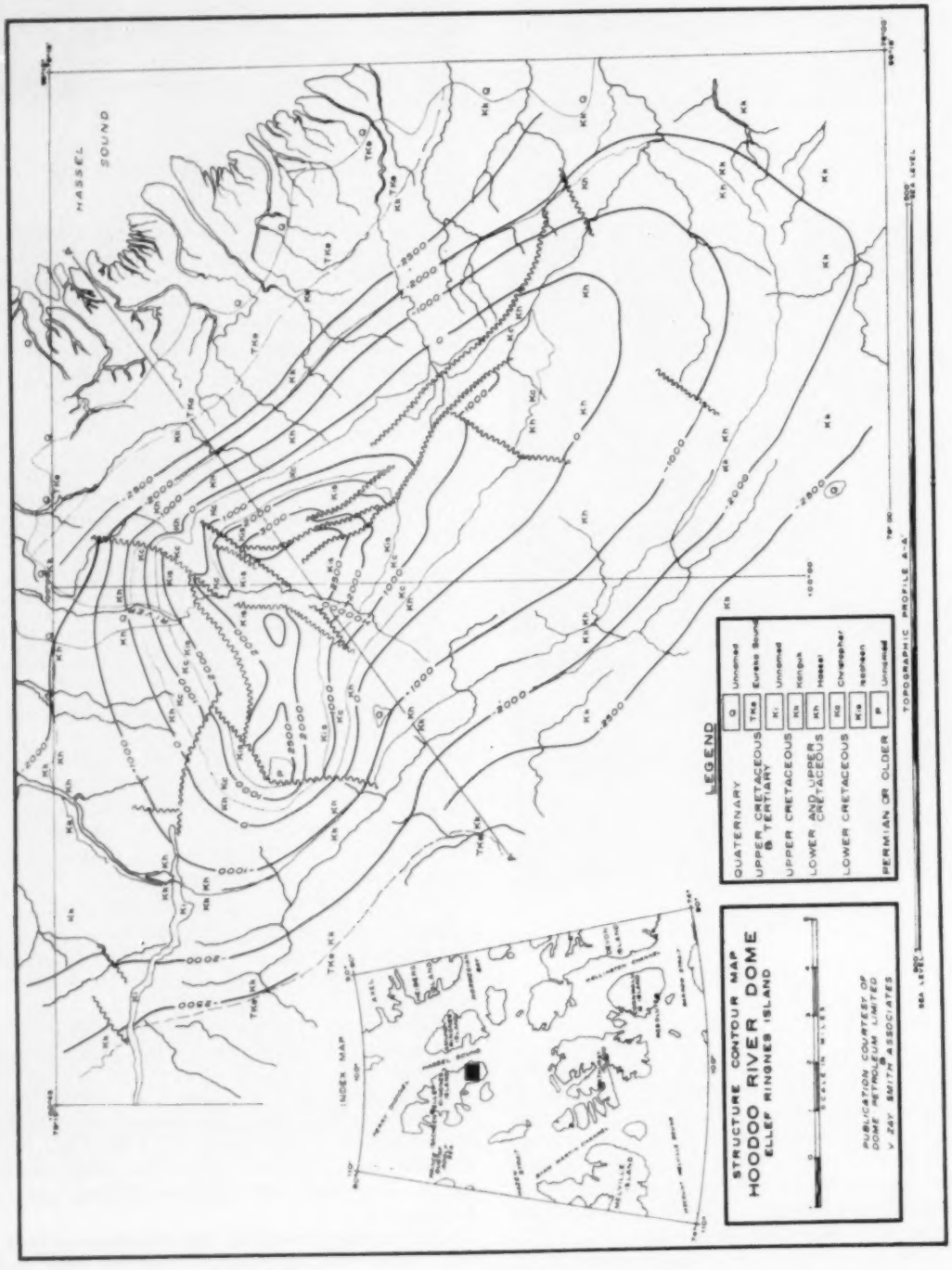

HASSEL SOUND
LEGEND
QUATERNARY
UPPER CRETACEOUS & TERTIARY
UPPER CRETACEOUS
LOWER AND UPPER CRETACEOUS
LOWER CRETACEOUS
PERMIAN OR OLDER
STRUCTURE CONTOUR MAP
HOODOO RIVER DOME
ELLEF RINGNES ISLAND
PUBLICATION COURTESY OF DOME PETROLEUM LIMITED
V. ZAY SMITH ASSOCIATES
INDEX MAP
TOPOGRAPHIC PROFILE A-A'

FIG 16

micro oil assay of a small sample of dolomite has given an oil content of 3·2 Imperial gallons per ton.

(viii) The basal limestone conglomerate of the Disappointment Bay formation on the north coast of Cornwallis Island, as well as the graptolitic limestone underlying the conglomerate, contain patches of a soft bitumen that has been identified as native asphalt.

(ix) There is bituminous limestone in the Ellesmere Fold Belt at Cape Baird on the east coast of Ellesmere Island, while at Lake Hazen ozokerite or some similar substance can burn like tallow.

(x) On Devon Island massive Allen Bay beds are commonly porous, with solid bitumen filling the pores, and in many cases the rocks emit a fetid odour when broken.

(xi) At another point on Devon Island there is an outcrop of fetid massive brownish dolomite belonging either to the Cornwallis or the Allen Bay formations.

(xii) At Dundas Harbour on eastern Devon Island there are 5 feet of Middle Cambrian rock and as much as 100 feet of Lower Ordovician limestone with petroliferous odours.

Recent Survey Works

(i) *Cornwallis Island.*—Recent geological work on Cornwallis Island has confirmed that the Allen Bay formation in the neighbourhood of Resolute Bay is a porous dolomite sometimes with much solid bitumen and very often possessing a strong petroliferous odour. It has similarly been found that the Read Bay limestone in the same area emits a fetid or petroliferous odour when struck. At a stream cutting across the axis of the Midshipman anticline on the northwest part of Cornwallis Island a 4-foot bed of crystalline, very porous limestone of the Cape Phillips formation has been found below the concretionary zone with a fair amount of oil staining, while the concretions themselves appeared to be oil stained and gave a very distinct petroliferous odour.

(ii) *Bathurst Island.*—Work on Bathurst Island has revealed that the Bird Fjord sandstone on Bracebridge Bay Island was entirely saturated with heavy tar and bitumen, while at another locality on the south limb of the Bracebridge anticline a specimen of a colonial coral with good porosity had abundant oil staining. An important point is that the widespread Cornwallis formation was found in eastern Bathurst to have small vugs that were completely filled with bitumen. The Variscan anticline towards the southwest part of the island has a reef mass with good porosity and oil staining near the base of the Blue Fjord, while at the base of the Bird Fjord a zone of fossils with fair oil staining continuously gave off a distinct petroliferous odour when freshly broken. In fact, it can be said that there are signs of petroleum substances—sticky asphalt, solid bitumen, oil staining, or petroliferous odours—in all ten of the exposed Palæozoic formations of Bathurst Island, ranging as they do from Middle Ordovician Cornwallis formation up to Upper Devonian Okse Bay formation.

(iii) *Melville Island.*—In the upper part of the Middle Devonian limestone exposures east of Weatherall Bay dried bitumen has been found in a quite extensive porous section, together with some in lower dolomites.

NAVIGATION CONDITIONS IN CANADIAN ARCTIC WATERS

Winter Conditions

Surface navigation in Arctic waters is not feasible during the winter months because of the formidable cover of ice in all channels and inlets. In some areas this ice may be present in the form of a solidly cemented sheet, and in others it may exist as broad fields of heavy floes constantly in motion under the influence of wind and tide but so densely packed that no passage, even to ice-breakers, would be possible.

Depending on the direction of the wind, lanes of open water may persist in certain areas, while in other places factors such as currents or salinity density differences may enable some parts to remain unfrozen throughout the winter. Unfortunately, navigation between one water region open throughout the winter and another is impossible.

Summer Conditions

The best conditions occur in the east and south, where the one year old ice cover of such areas as Hudson Bay, or the moving local pack of Baffin Bay may usually be counted upon to clear in the course of the summer, while the most unfavourable conditions are found in the northwest near the Arctic Ocean, where the ice extending northeastwards from the northern shores of Prince Patrick and Melville Islands past the Ringnes Islands up to a zone close to west Axel Heiberg Island, may loosen slightly but is never known to clear.

The south flowing Canadian current in Baffin Bay and Davis Strait runs along Baffin Island, packing ice heavily against its shores. Similarly, in east–west tending straits, such as the Parry Channel, the eastbound current, aided by prevailing northwest winds, presses its concentration of ice against the southern shores. Break-up depends not only on the temperature and the amount of sunlight but also on the strength and direction of the wind, and thus it is inevitable that optimum conditions cannot occur simultaneously in all parts of such a vast region.

The first of five ice maps (Fig 17) indicates the best conditions likely to prevail in the various areas of the Queen Elizabeth Islands in light ice years, while the second (Fig 18) shows the conditions which may be present in unfavourable years. The actual pattern of summer ice distribution for any particular year would be some combination of these two extremes.

It will be observed that in a good summer season

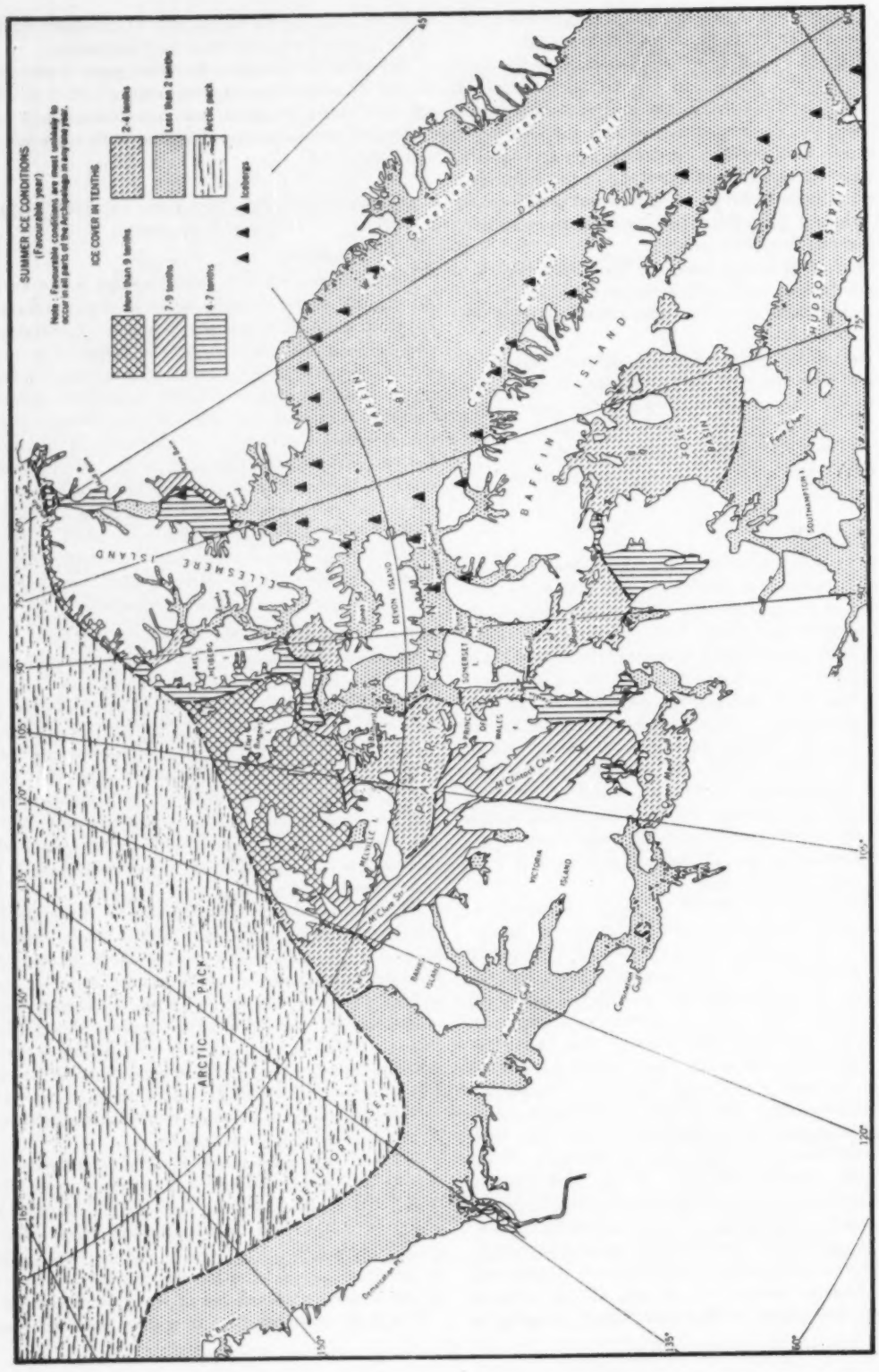

SUMMER ICE CONDITIONS
(Favourable year)
Note: Favourable conditions are most unlikely to occur in all parts of the Archipelago in any one year.
ICE COVER IN TENTHS
More than 9 tenths
7-9 tenths
4-7 tenths
2-4 tenths
Less than 2 tenths
Arctic pack
Icebergs
DAVIS STRAIT
BAFFIN BAY
BAFFIN ISLAND
HUDSON STRAIT
ELLESMERE ISLAND
DEVON ISLAND
SOMERSET I.
PRINCE OF WALES I.
VICTORIA ISLAND
BANKS ISLAND
ARCTIC PACK
BEAUFORT SEA

FIG 17

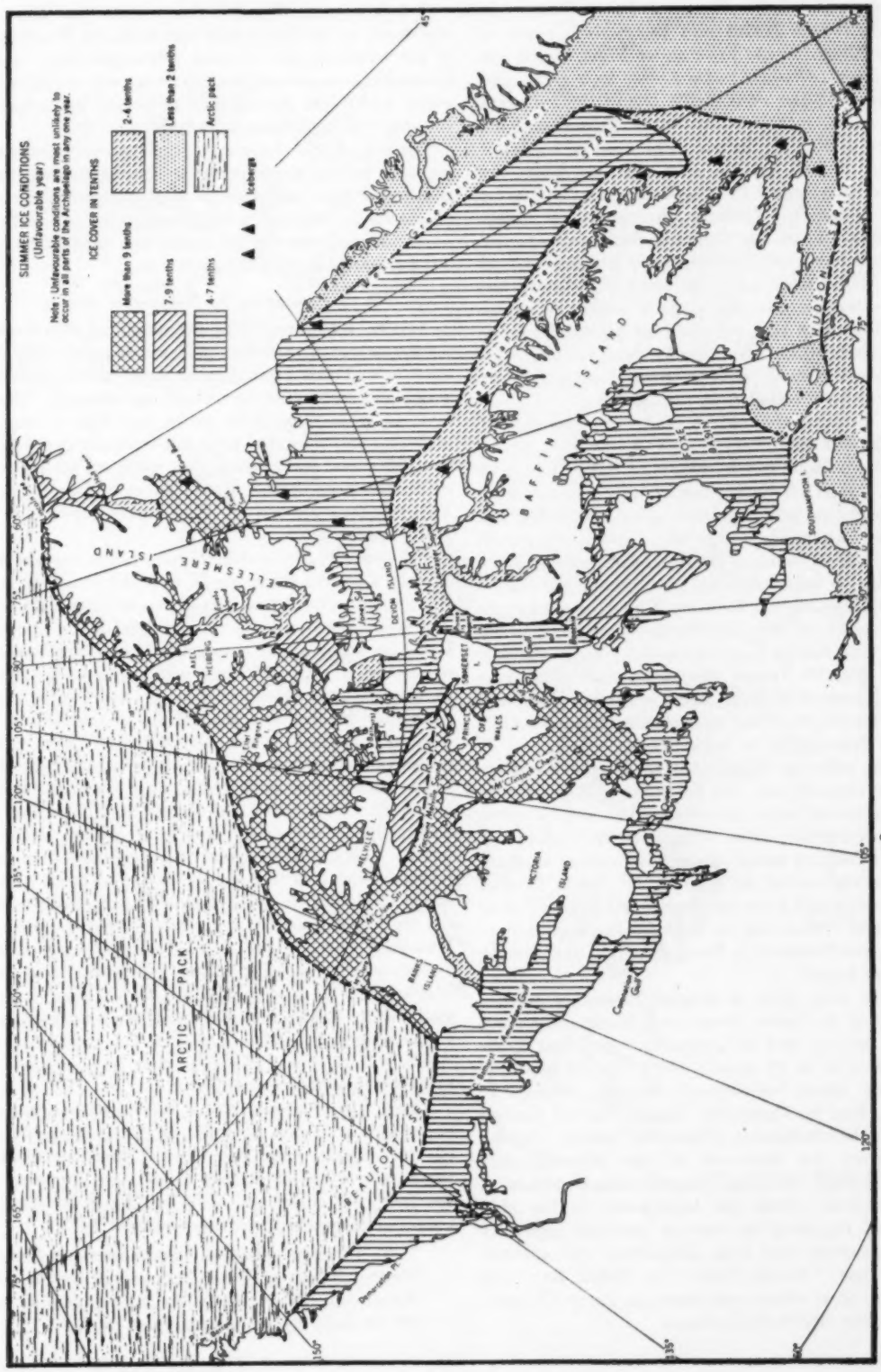

SUMMER ICE CONDITIONS
(Unfavourable year)
Note : Unfavourable conditions are most unlikely to occur in all parts of the Archipelago in any one year.
ICE COVER IN TENTHS
More than 9 tenths
7-9 tenths
4-7 tenths
2-4 tenths
Less than 2 tenths
Arctic pack
Icebergs
BAFFIN BAY
DAVIS STRAIT
BAFFIN ISLAND
FOXE BASIN
HUDSON STRAIT
ELLESMERE ISLAND
DEVON ISLAND
SOMERSET
PRINCE OF WALES
VICTORIA ISLAND
BANKS ISLAND
ARCTIC PACK
BEAUFORT SEA
Greenland Current
Labrador Current
Hudson Bay
Southampton I.
Coronation Gulf
Dolphin and Union Strait
Amundsen Gulf
Prince Patrick I.
Melville I.
Cape Parry
Mackenzie R.
Mackenzie Bay
Darnley Bay
Dease Strait
Queen Maud Gulf
Committee Bay
Simpson Str.
Peel Sound
Franklin Str.
Parry Channel
Barrow Str.
Lancaster Sound
Jones Sound
Nares Str.
Kane Basin
Kennedy Channel
Smith Sound
Hall Basin
Robeson Channel
Kane Sea
Lincoln Sea
Wandel Sea
Greenland
45°
60°
75°
90°
105°
120°
135°
150°
165°
180°
135°
120°
105°
90°
75°
60°

Fig 18

Davis Strait and Baffin Bay, and Parry Channel as far as Cornwallis Island and the eastern coast of Bathurst Island, would have an ice cover that is less than two-tenths, while farther west to a point just past Bridport Inlet on Melville Island the ice cover would be two-tenths to four-tenths, thus permitting that part of Melville Island to be readily accessible to ships. It will also be seen that no difficulties would be encountered in approaching and sailing up Eureka Sound to Fosheim Peninsula, for Jones Sound would have less then two-tenths, Norwegian Bay would have only two-tenths to four-tenths, and Eureka Sound right up to its head would have less than two-tenths. At this stage it might be appropriate to mention that ice coverage amounting to as much as six-tenths or seven-tenths should be navigable by ice-strengthened vessels sailing alone, or by ordinary ships if escorted by ice-breakers.

In an unfavourable year a heavy concentration of pack—the "Middle Pack" of unhappy memory to whalers—would lie in the middle of Baffin Bay with an ice coverage amounting from four-tenths to seven-tenths, and this would present some difficulties, but should nevertheless be navigable. The eastern part of Parry Channel, south of Devon Island, would have two-tenths to four-tenths ice cover, while the waters around Cornwallis and Bathurst Islands westwards to the east coast of Melville Island would have an ice cover of four-tenths to seven-tenths. Thus, the east coast of Melville Island should be reached, but as the south coast of Melville Island in such a year would have an ice cover of from seven-tenths to nine-tenths, Bridport Inlet might be inaccessible.

Dealing with the approaches to Eureka Sound in the unfavourable year, the ice cover in Jones Sound would amount from four-tenths to seven-tenths, eastern Norwegian Bay lying off the southwest coast of Ellesmere Island would have a cover amounting to seven-tenths to nine-tenths, while Eureka Sound itself would have only two-tenths to four-tenths of ice cover. The difficult part for the approach to Fosheim and Mokka is in Norwegian Bay to the south of Eureka Sound.

Another map gives a detailed record of the ice distribution in Davis Strait and Baffin Bay from 5 to 14 August, and in Lancaster Sound and Jones Sound from 15 to 20 August 1958, (Fig 19) when the *D'Iberville* made her annual resupply voyage to Resolute Bay on Cornwallis Island, and to Eureka Sound in north-western Ellesmere Island. During this journey ice observers of the Meteorological Branch carried out long range reconnaissances in RCAF aircraft, while the helicopters on the ship were used regularly for shorter scouting trips. It will be observed that some difficulties were encountered in the "Middle Pack" in Baffin Bay, but thereafter open water was found in Parry Channel, Resolute Bay, and in Jones Sound.

A fourth map (Fig 20) shows that the ship encountered ice covering only one-tenth to five-tenths in the southern part of east Norwegian Bay, while in the northern part of the Bay there was ample open water which had increased considerably by the time the ship returned three days later.

The last of these ice maps (Fig 21) records that during the voyage northwards in Eureka Sound itself there was open water in its southern part and only one-tenth to five-tenths ice coverage in its northern part. During the voyage south two days later even more favourable conditions were met.

Possibility of Prolonging the Navigation Season

Naturally data regarding the length of time vessels could navigate between Ellesmere and Melville Islands and the permanently open North Atlantic waters off southwest Greenland are meagre. However, of great importance is the fact that a convoy including an oil tanker does sail regularly every year from Montreal to Resolute Bay while an ice-breaker sails each year farther north to re-supply Eureka. The repeated success of this convoy operation is most noteworthy.

The annually renewed Baltic ice reaches a maximum of only 3 feet in thickness as opposed to about 6 in the channels of southeastern Queen Elizabeth Islands. Moreover, the former is usually land fast while the latter in many parts is constantly moving because of currents. Nevertheless, it would appear that some of the navigational conditions in the Baltic could have some bearing on Canadian Arctic matters. For example, Finland keeps her southern ports open even in the most severe winters by means of powerful ice-breakers. One such vessel is the *Woima*, 274 feet long with a beam of 63 feet 6 inches and a draft of 21 feet, propelled by diesel electric machinery with an ihp of 10,500. This vessel has two propellers aft, together with two forward which are of great assistance. However, in view of the risk of encountering old thick polar ice that may have moved southwards into some parts of the channels and sounds of the Canadian eastern Arctic waters, bow propellers probably cannot be used in that region. These Finnish ice-breakers have assisted normal ocean tankers into Finnish ports in mid-winter, but for the Canadian Arctic waters it would appear that ice-strengthened tankers would be a necessity.

There has, however, been very little practical experience with ice-strengthened tankers anywhere in the world; moreover, there are considerable variations in ice conditions from year to year, so the following comments on a prolonged navigation season are presented with reservations:

(i) It seems possible that Lancaster Sound, Barrow Strait, and the northern part of Melville Sound in favourable years are navigable for 69–90 days by ice-strengthened vessels.

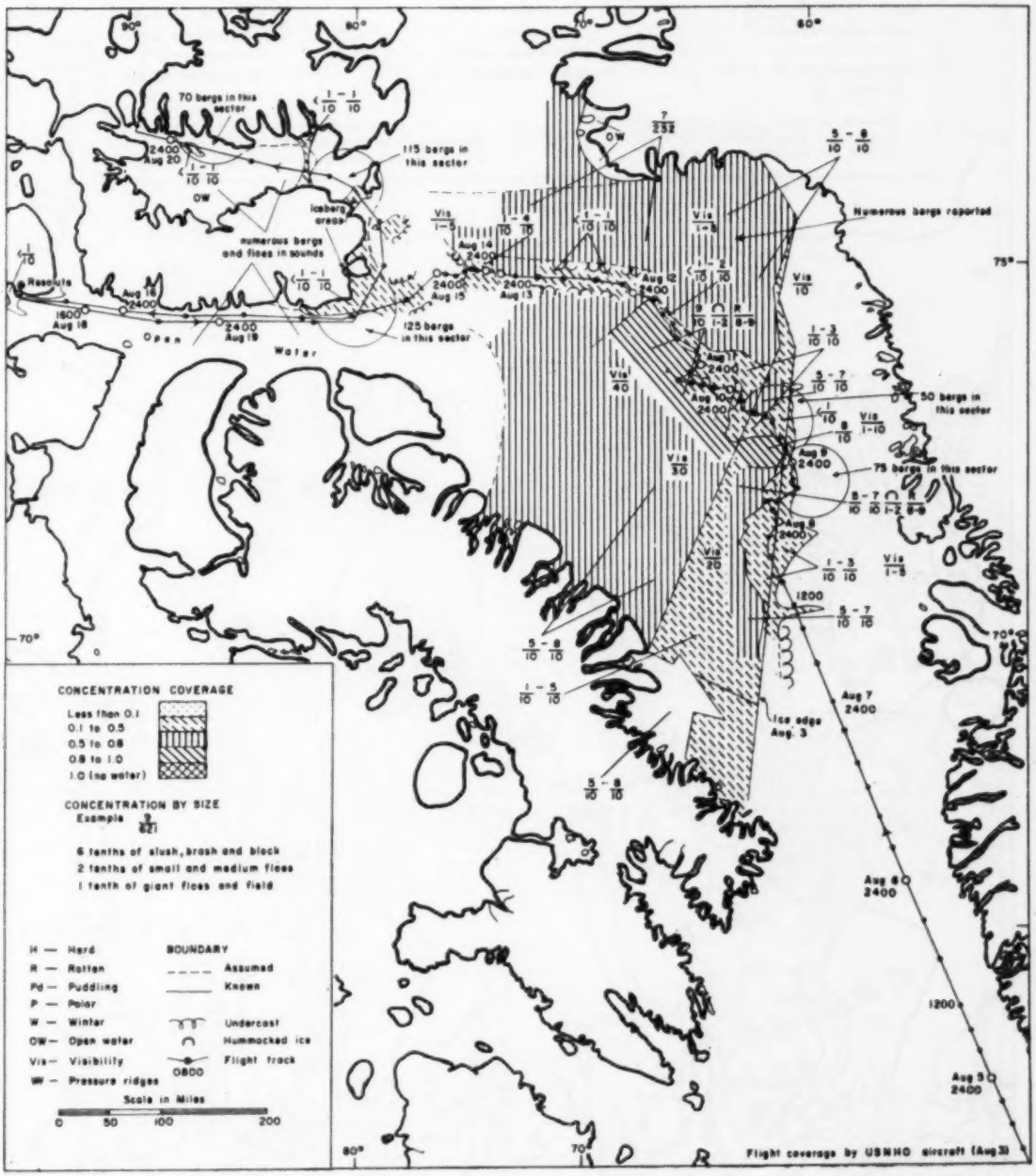

90°
80°
70°
60°
75°
70 bergs in this sector
115 bergs in this sector
125 bergs in this sector
50 bergs in this sector
75 bergs in this sector
Numerous bergs reported
numerous bergs and floes in sounds
Icebergs
Open Water
Ice edge Aug. 3
Aug 7 2400
Aug 8 2400
Aug 9 2400
1200
Flight coverage by USNHO aircraft (Aug 3)
CONCENTRATION COVERAGE
Less than 0.1
0.1 to 0.5
0.5 to 0.8
0.8 to 1.0
1.0 (no water)
CONCENTRATION BY SIZE
Example 7/621
6 tenths of slush, brash and block
2 tenths of small and medium floes
1 tenth of giant floes and field
H — Hard
R — Rotten
Pd — Puddling
P — Polar
W — Winter
OW — Open water
Vis — Visibility
W — Pressure ridges
BOUNDARY
Assumed
Known
Undercast
Hummocked ice
Flight track
0800
Scale in Miles
0 50 100 200

FIG 19

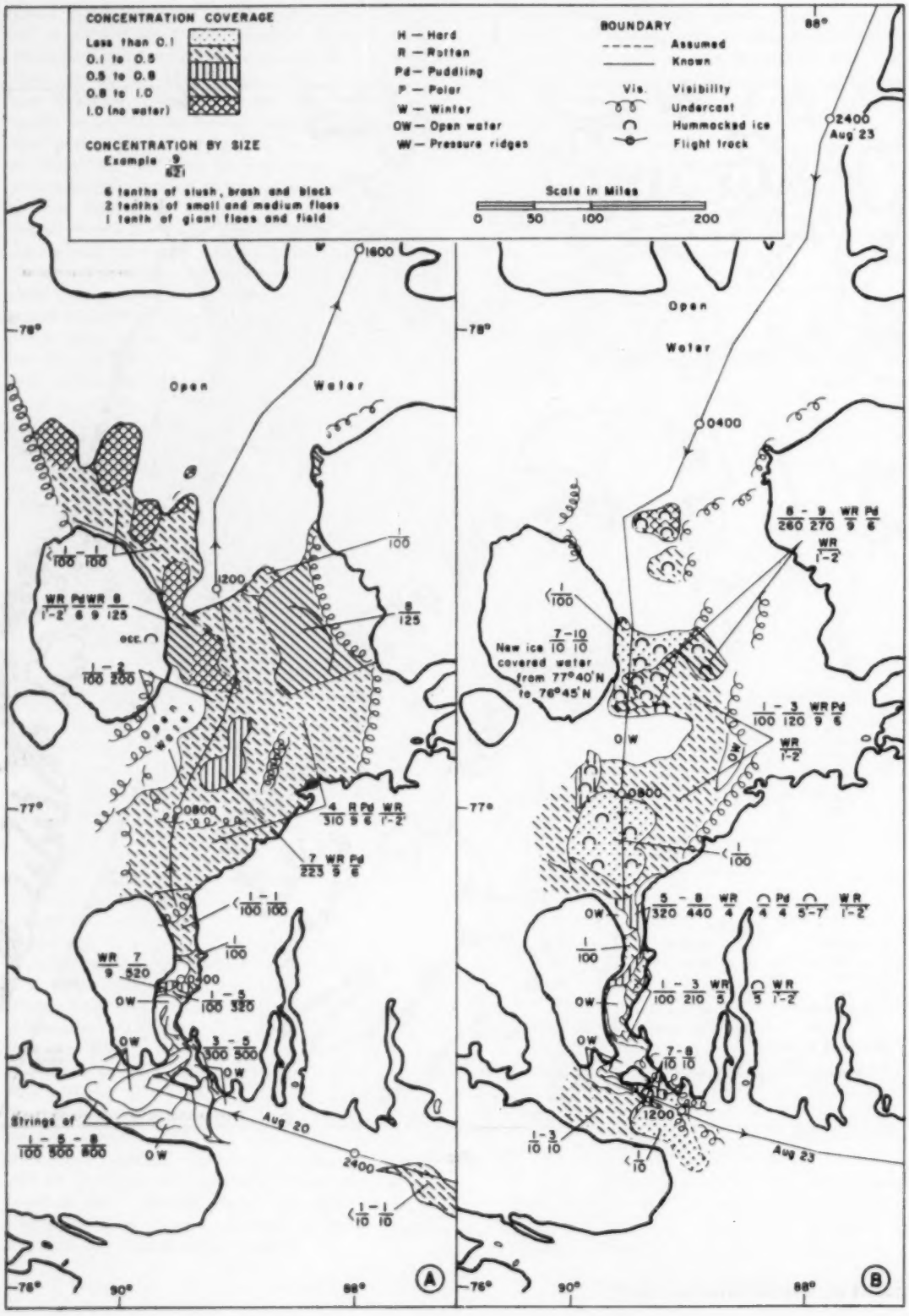

CONCENTRATION COVERAGE
Less than 0.1
0.1 to 0.5
0.5 to 0.8
0.8 to 1.0
1.0 (no water)
CONCENTRATION BY SIZE
Example 9/621
6 tenths of slush, brash and block
2 tenths of small and medium floes
1 tenth of giant floes and field
H — Hard
R — Rotten
Pd — Puddling
P — Polar
W — Winter
OW — Open water
RW — Pressure ridges
BOUNDARY
Assumed
Known
Vis. Visibility
Undercast
Hummocked ice
Flight track
Scale in Miles
0 50 100 200
Open Water
New ice 7-10/10 covered water from 77°40'N to 76°45'N
Strings of 1/100 5/500 8/800
Aug 20
Aug 23
1600
1200
0800
0400
2400
78°
77°
76°
90°
88°
A
B

Fig 20

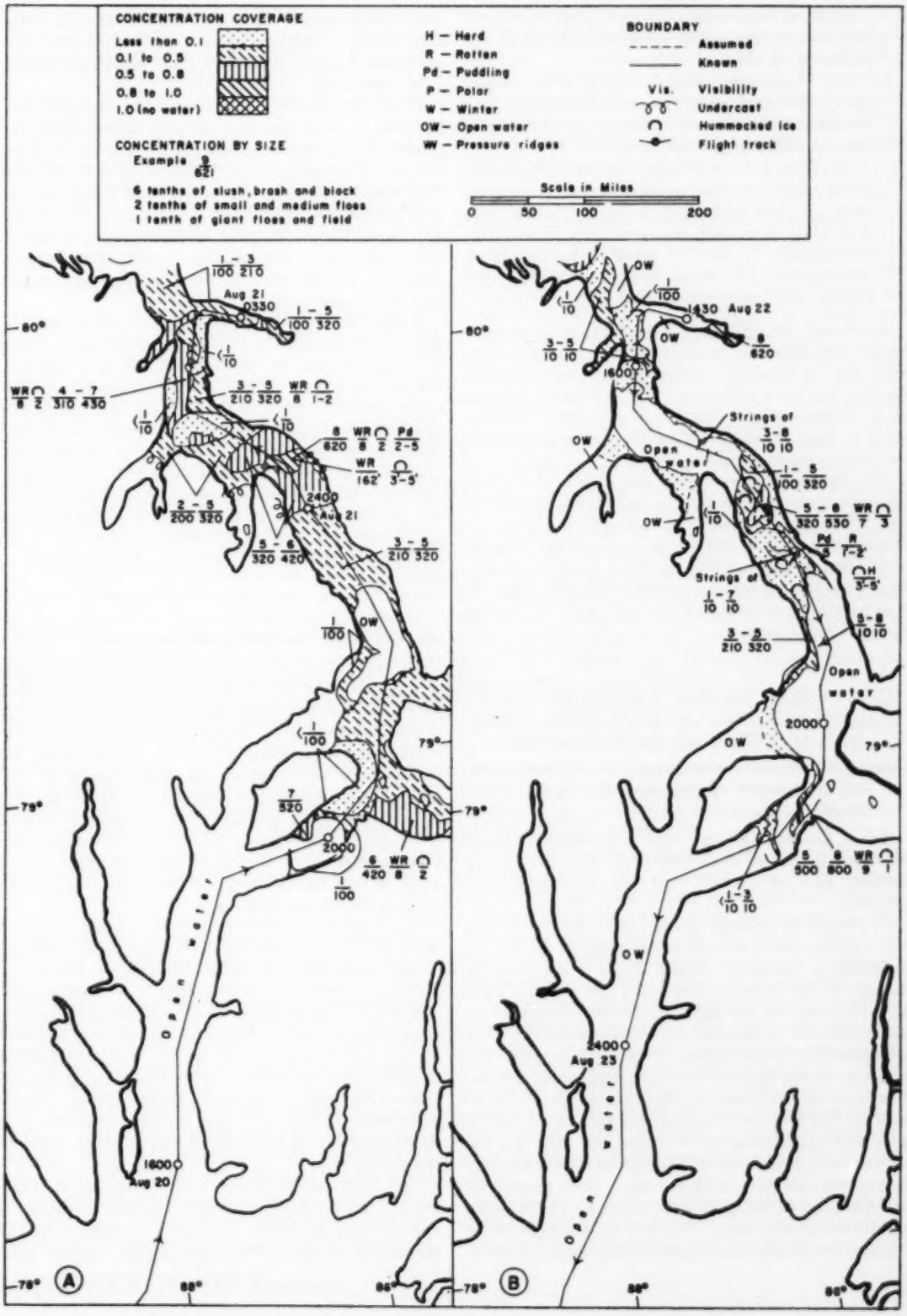

CONCENTRATION COVERAGE
Less than 0.1
0.1 to 0.5
0.5 to 0.8
0.8 to 1.0
1.0 (no water)
CONCENTRATION BY SIZE
Example 9/621
6 tenths of slush, brash and block
2 tenths of small and medium floes
1 tenth of giant floes and field
H — Hard
R — Rotten
Pd — Puddling
P — Polar
W — Winter
OW — Open water
WW — Pressure ridges
BOUNDARY
Assumed
Known
Vis. Visibility
Undercast
Hummocked ice
Flight track
Scale in Miles
0 50 100 200
Aug 21
0330
2400
Aug 21
2000
1600
Aug 20
1430 Aug 22
1600
2000
2400
Aug 23
Strings of
Open water
Strings of
Open water
OW
80°
79°
78°
88°
86°
A
B

Fig 21

(ii) Even with vessels of this type it is unlikely that navigation can be opened much before the beginning of August.

(iii) The season could possibly be prolonged up to 120 days with the use of powerful ice-breakers, but it is too optimistic to consider a season as long as five months.

(iv) There is no experience with ice-strengthened ocean-going tankers working under conditions such as those prevailing in Arctic Canada, but it is likely that with the assistance of powerful ice-breakers it will be possible to use these specially designed ocean tankers in these regions during the forementioned period.

In connexion with this last point, it is of vital importance that the tankers have a smaller beam than the ice-breakers, otherwise they are liable to sustain very heavy damage. The approximate beam of a 16,000-ton dw tanker is 65 feet. Another point to bear in mind is that the longer the vessel, the less its manœuvrability in ice.

The Canadian Government has a fleet of ten ice-breakers, five of them having been built during the last three years. The most recent is the *John A. Macdonald*, of 6186 gross tons and having a length of 315 feet, a beam of 70 feet, and a draft of 28 feet. It is propelled diesel electrically by 15,000 shp. It is of particular interest to note that she has a cruising range of 20,000 miles.

THE PROSPECTS FOR THE PRODUCTION AND MARKETING OF PETROLEUM FROM THE QUEEN ELIZABETH ISLANDS

Government Regulations Respecting the Administration and Disposition of Oil and Gas in the Queen Elizabeth Islands

The "Canada Oil and Gas Regulations" came into force on the 13 April 1960 and apply to all lands forming part of Canada that are not within any province.

A permit is granted giving permission to carry out exploratory work on lands applied for by an exploratory company. Apart from a small fee, a deposit to the value of five cents per acre for each acre included in the area for which application is made has to be handed to the Government as a guarantee for expenditures in exploration that will be made during the first half of the term of the permit. The term of the permit is six years at five cents an acre for the first three-year period and an additional guarantee amounting to 25 cents per acre for the second three-year period. Thereafter, the permit may be renewed annually, with increasing work guarantees of 30, 40, and 50 cents per permit acre for the seventh, eighth, and ninth years. The required work guarantee remains at this fifty cent figure for the tenth, eleventh, and twelfth years. These deposits are returned to the exploratory companies once actual exploration expenditures up to or exceeding the required amounts have been made.

Land held under a permit may be changed to a 21 year oil and gas lease at any time during the permissible 12 years permit period, but in so doing certain "Canadianization" clauses have to be met. The main features of these are that leases will be only granted to companies incorporated in Canada, and these companies must be listed on a Canadian Stock Exchange, thus giving Canadians the opportunity of participating in the financing and ownership of the company.

Under the present regulations one-half of the permit acreage may be held as a lease while the other half is returned to the Government for disposal, usually by public auction. This is the Crown Reserve system in force in the Canadian provinces and carries with it many features that preclude efficient methods of production. However, it seems likely that a joint development scheme will be put into effect whereby the area surrendered as Crown Reserve will be offered back to the company which held the land originally, and be operated by it under terms equitable to both the Crown and the discoverer of the oilfield.

Geological and Photogeological Operations

Numerous detailed geological papers and maps dealing with the Queen Elizabeth Islands have been prepared and published by the Geological Survey of Canada since 1954, so considerable regional information has been made available. In addition, the Government of Canada has made available trimetrogon photographs of the islands taken by the RCAF some years ago, and also a complete vertical coverage of photographs taken more recently. All these matters have been of tremendous assistance to those in the oil industry who are now engaged in seeking petroleum in the area.

The exploration technique that is being followed is to first carry out a detailed photogeological analysis of the lands and then follow this up by sending in geological field parties to verify the photographic structural interpretations and to obtain stratigraphic information as well. The field work is then followed up by photogrammetrical studies of the structures to determine the amount of vertical and horizontal closure that exists. This system is working exceedingly well, and a vast area is being explored at a speed that would not be possible in other parts of the world.

The field parties have been using small Piper Super Cubs equipped with large balloon tyres which enable them to land practically anywhere in the exploration region, even though the surface may

often be stony and rocky. The season without snow cover lasts from about mid-June to early September and, being daylight for the full 24 hours, a considerable amount of work can be accomplished. However, delays do occur due to fog and other conditions unsuitable for flying.

The structures are being most clearly delineated, and thus it is believed that geophysical methods can be dispensed with, at this stage at any rate; it thus follows that the next step could well be the testing of the structures by drilling exploratory wells.

Drilling Operations

It is believed that the design of the rig equipment should be based on the assumption that several exploratory wells will be required to be drilled to 8000–10,000 feet, with maybe one or two wells still deeper down to 13,000–15,000 feet. These requirements could be met with a rig such as a National Ideal 55 A, or an Ideco H.525, using 4½-inch drill pipe down to 10,000 feet and 2⅞-inch for the deeper portion of the deep tests. By keeping the rig size to a minimum, initial investment will be kept down and transportation costs—the freight to the islands and the rig moves between the islands—will be held as low as possible. Most of the potential oil structures are close to sea-water channels that open up every year for a period, so navigation between the Atlantic and the islands is possible. With British ports only 3000 miles away, it seems logical that the rig should be shipped from Britain and unloaded by pontoons on to beaches close to the scene of operations. Along with the "winterized" rig would be all the other items—transport, camp buildings, casing, mud, cement, food supplies, and fuel. Sufficient expendables would have to be brought in by sea to keep operations going from one navigable season to another. All this material, totalling a little less than 3000 tons, could be shipped in one of a fleet of Danish polar vessels specially strengthened and designed to operate in ice filled waters.

The drilling crews should be recruited from Western Canada, where there are several Canadian drilling contractors who have already had operating experience on the mainland of Arctic Canada.

The drilling procedure would be the same as that used in Northern Canada except that it would be necessary to set surface casing to 1500 feet to make sure all the perma-frost was cased off. About 50 feet of 22-inch conductor pipe would be first set, followed by a surface hole drilled to 1500 feet, using mud at a temperature close to its freezing point in order to reduce the thawing of the perma-frost. Surface pipe of 13⅜-inch od would then be cemented to surface using a low temperature cementing technique, but thereafter a routine programme would be adopted. During a full twelve month drilling period two wells down to 12,500 feet should be drilled at a cost of about $2 million, or alternatively six wells to 6000 feet in the same period should be possible at a similar total cost. If it is initially considered advisable to avoid drilling during mid-winter and drill for only seven months the expenditure should be around $1·2 million, with a proportional reduced amount of footage being drilled.

Petroleum Production and Marketing Prospects

Obviously the logical markets for petroleum produced from the Queen Elizabeth Islands are the British Isles and Western Europe some 3000 miles away, together with the Maritimes of Canada and Montreal, again some 3000 miles away (Fig 22). However, equally obviously one difficulty about marketing oil from these islands is the fact that the seaways in the vicinity of the potential oil-bearing structures are open to navigation for only a short and limited period in each year. Nevertheless, the fact remains that certain channels in the Queen Elizabeth Islands are currently being used by ships from Montreal every year, and it thus follows that some oil could be shipped eastwards by tanker during each season immediately following the discovery of oil. This is a situation considerably different from that pertaining to certain landlocked areas, where even though the chances of finding oil in prolific quantities may be great, the reserves of oil that would have to be established before a long distance pipeline could be financed would be considerable.

In this connexion it is noteworthy that the majority of the structures in the Eureka, Parry Island, or Cornwallis Fold Belts are within 25 miles of sea-water channels that open up seasonally for navigation. It thus follows that the amount of finance that will be required to pipeline the oil from wellhead to tanker will be relatively small.

In an earlier section dealing with ice conditions in Canadian waters, the conclusion had been reached that ice-strengthened ocean going tankers assisted by ice-breakers could reasonably be expected to ship oil out for four months in the year. Naturally, however, an irregular supply is not so convenient from a refinery and marketing standpoint, and would be of less strategic importance than a supply that is spread evenly throughout a full year. In connexion with this, nuclear-fuelled oil-carrying submarines working throughout the year come to mind. However, they are not brought into this discussion on account of the fact that, like landlocked areas, considerable reserves of oil would have to be established before the financing of a fleet of them could be contemplated.

In order to overcome the irregularity of supply by surface tanker it is suggested that storage be installed at some intermediate place adjacent to sea water

that is open the whole year round. Large earthen storage reservoirs, much cheaper to construct per barrel of capacity than steel tanks, could be built in southwest Greenland in the neighbourhood of God-

Detailed studies into the economics of a transportation system such as that just outlined will have to be made after oil has been discovered, but it is nevertheless firmly believed that if large oil-bearing

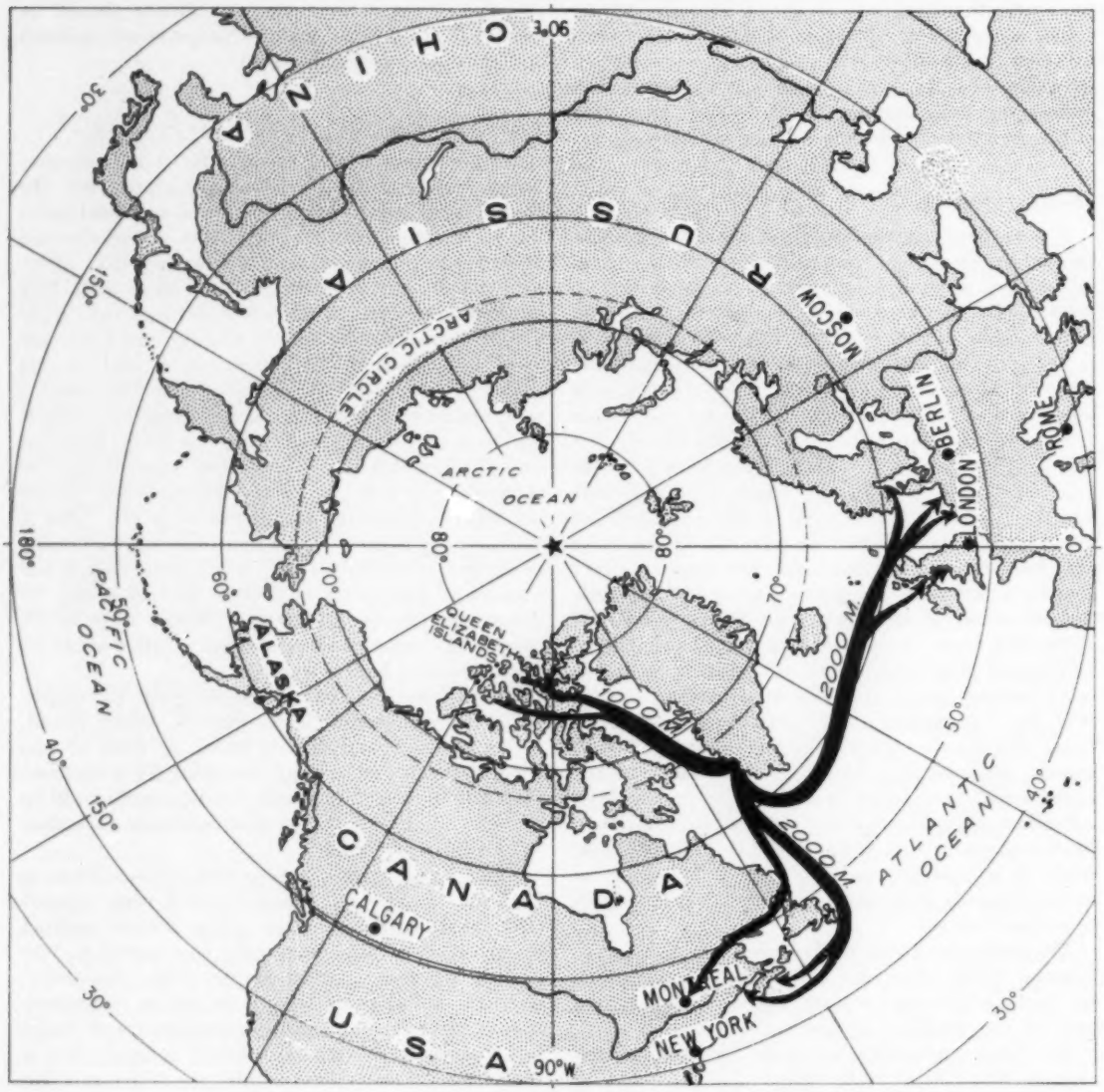


FIG 22

MARKETS FOR POTENTIAL QUEEN ELIZABETH PETROLEUM PRODUCTION

Intermediate storage in SW Greenland

thaab, where North Atlantic waters are always navigable. Reservoirs such as contemplated could store oil in sufficient quantity to supply the markets for the eight months closed to Arctic navigation, and be drawn on by normal ocean-going tankers.

structures are found with conditions permitting wells to be widely spaced and each of them being capable of flowing at sustained high rates, then the extra costs of navigating in ice waters and of handling at the intermediate storage point could be absorbed and

still allow the oil to be competitively sold on the markets of the world.

Conclusion

Suitable petroleum source and reservoir rocks of all ages are known to be present, there are plentiful signs of petroleum substances, large folded structures many miles long and wide suitable for the entrapment of oil have been found, and a plan has been outlined whereby crude could be economically supplied to world markets initially for a limited period and later throughout the whole year by surface tanker. It is thus to be hoped that in the relatively near future drilling operations may start and result in a flow of oil to international markets in such quantities that it will be said that yet another major oil producing area of the world has come into being—the Queen Elizabeth Islands.

ACKNOWLEDGMENTS

It is indeed a pleasure to acknowledge the great help that has been given by the Government of Canada to those now actively engaged in oil exploration in the Queen Elizabeth Islands. The many reports of the Geological Survey of Canada published by the Department of Mines and Technical Surveys, and the complete coverage of the area by vertical aerial photographs have been of tremendous assistance. Without them, and without the advice and help given by the Minister and officers of the Department of Northern Affairs and National Resources, exploration for petroleum in the islands would not have advanced nearly so rapidly as it actually has.

Finally, the author would like to thank the staff of Round Valley Oil Co. for their assistance in the work described in this paper, and the Boards of Lobitos Oilfields Ltd and C. T. Bowring Ltd for permission to publish this information.

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DISCUSSION

F. E. Wellings: At a time like this, when there is a world surplus of production capacity (affecting Canada more than most producing countries) and which is already causing curtailment of exploration, companies must consider carefully the costs of finding the additional reserves which will be needed in the next decade. Have any economic studies been made here to find out what size of oil reserves is required to pay off, given the logistics already described?

The aerial photos and photo-geological maps, together with the splendid obliques in the Canadian Geological Survey paper in the *AAPG Bulletin* in 1954, remind me of similar aerial photos of folded Palæozoics in the Hoggar Mountains of Southern Sahara (substituting snow for sand, of course). Its Cambrian sandstones are now producing, and it is useful to cast one's mind back ten years in North Africa and to recall how little interest was shown then in the Sahara and Libya, in spite of the folded sediments south of the sand. The Queen Elizabeth Islands do not have live seepages, only fœtid limestones and bituminous shales, but neither does the Sahara or Libya, although the thick permafrost here may have prevented the escape or detection of seeps.

Mr Cameron has quoted ample thicknesses of possible reservoir, cover, and source rocks in various basins, and there appear to be enough accessible structures already mapped by photo-geology and photogrammetry for testing to begin without geophysics. It is typical of oil prospecting that the most accessible structures seem to be the deepest exposed, and that the Sverdrup Basin on the Arctic Ocean, where the section is thickest, has the surface Cretaceous flat and the most unfavourable climatic conditions. Are the piercement plugs here prospective themselves?

Finally, does the author think that the Crown reserve system applied over these big structures will lead, as on

the mainland, to waiting for auction of the discarded halves.

A. Bryce Cameron: I think that Mr Wellings' remark about the permafrost might well prove to be true. The permafrost in this region is said to go down to about 1200 feet, and that itself might form a considerable cap, even in an outcrop of a porous rock, and form a trap there.

Regarding the question of reserves, two gentlemen have calculated reserves based on the volume of sediments—based on the ratio of sediment in the U.S.A. and discovered oil—and some large reserve figures have been presented in the press. I do not know what the economic limit for research should be, but we have an idea that the rate of production per well should not be the 50 bd that we have in Alberta, but ought to be about 1000 bd, which is not a very high figure really, bearing in mind Middle East figures and so on. In fact, but for prorationing, quite a number of Alberta wells can flow at 1000 bd from limestone formations. The formations in the Queen Elizabeth Islands are limestone and dolomite in most cases—certainly all the palæozoics are—and were folded and therefore well fissured. Thus high production rates can be expected. The 1000 bd rate per well could prove to be an economic daily minimum.

I do know that the Crown reserve system is incorporated in the regulations, but it is hoped by many parties, and may be supported by the Canadian Government, that the system of bonus payments, etc., for returned lands will not be put into effect. There is talk of a joint development scheme whereby the discovery company gets back the land returned to the Government on the basis of paying a higher royalty rate, or of doing exploratory work on the land. That aspect has not been settled, but if the Crown reserve system is put into effect, as in the provinces, then one has difficulties such as corridors across structures, and newcomers acquiring these lands through bonus payments followed up by unnecessary drilling. For example, in the Leduc field of Alberta there are 450 wells producing from the D3 when in fact about 50 wells would have been sufficient. It is hoped that more of a Middle East type of land situation can be developed up there—a system that would encourage wide spacing, very few wells, and the drilling of wells only when there is a need for them.

N. L. Falcon (The British Petroleum Co. Ltd): All oil geologists are interested in oil exploration anywhere where there could be prospects, and we all feel that in due course the Queen Elizabeth Islands will be explored. However, from the geological point of view there are far more things which ought to be known before an adequate assessment can be made.

For instance, the Parry Islands folds are extremely old; after formation they were planed off, covered over by the Permo-Pennsylvanian and higher formations, and then all the cover was stripped off. This of course is not a very favourable history, because there has been an enormous amount of time when any oil which may have been accumulated underneath could have escaped. There are many parts of the world with very attractive old anticlines in which there are no hydrocarbons.

Just before Christmas there was an interesting report in the press saying that the Russians in Siberia had been finding or looking for hydrocarbons under permafrost, and although it did not say what was going on, I think sufficient was said to make it possible to guess. I became interested in the effect of permafrost on seepages some time ago when I was asked to advise on the oil prospects of an area in East Greenland where there were some mud volcanoes. Also our little Formby oilfield in England has presumably been ice-covered—for all we know it may have actually accumulated where it is to-day underneath the ice or in the permafrost zone. Permafrost is not of the same thickness everywhere, and the thickness, I presume, depends on the local temperature gradients in the rocks near the surface; the iso-geotherms may be higher under anticlines than under synclines, so perhaps the permafrost zone is thinner under anticlines than under the synclines. In looking for actual evidence of liquid hydrocarbons in Mr Cameron's area, where there are anticlines which can be drilled to-morrow if one has the courage, I suggest consideration should be given to the possibility of bringing in a light rig, able to drill not very far below the bottom of the permafrost on whatever anticlines seem to have the best closures. There the iso-geotherm contours may also be closed and if there are any liquid hydrocarbons deeper down, some evidence of oil may be found even though they may not be commercial oil accumulations. If that was done, using a lightweight outfit able to drill to about 1000 feet, and a Formby type oil accumulation was found underneath the ice, the area would become much more attractive. I say that because the evidences of oil which there are in the Queen Elizabeth Islands now, while perfectly satisfactory, to the experienced oil explorer are not enough. Better indications can be found in the Midlands Valley of Scotland, the Pennines, and in Shropshire, but no significant oil has been found there, which suggests a need for caution in the difficult Arctic environment.

Dr P. E. Kent (The British Petroleum Co. Ltd): I had the pleasure of a trip to the same area in 1959, a briefer trip than those Mr Bryce Cameron enjoyed, but enough to obtain a general view of the Queen Elizabeth Islands in particular. I formed a favourable impression of this area as an oil prospect, if one could eliminate the geographical aspects. Palæozoics, for example, have excellent reservoir rocks—there are very thick dolomites with good porosity, smelling of oil, great thicknesses of source rocks, and on the whole there appears to be remarkably little evidence of Palæozoic induration or that the rocks have been too greatly maltreated for oil country. There is every chance, in fact, that where there is a coincidence of cover and suitable reservoirs, oilfields may be found at depth. I think that some degree of optimism is quite well justified in regard to this region.

But 1959 was a bad ice year, and it was quite appreciably worse than the map which Mr Cameron has included. Resolute, as we have been told, is the main supply base for the Queen Elizabeth Islands, but in 1959 there was a question until late in August whether the convoy would get through at all. It was iced-in 100 miles out, and two ice-breakers, which at the time were the most powerful in Canada, all but failed to get the convoy through. In fact the wind changed, the ice eased up, they got through, and were given a maximum of three weeks to unload, which was rather longer than needed.

Resolute is the most accessible point of the islands for the use of motor transport. Bradstock Bay is a possible alternative base. But that is a long way short of reaching Melville Island, the winter harbour which Parry reached. Of course, Parry did this sort of thing in a sailing boat, whereas nowadays the ships that go there have the advantage of very considerable horsepower, but the above does illustrate the fact that one has to go prepared for much limitation or intermittent interference with communication. This is a factor which will, in the long run, increase the expenses of the operation, and will add a rather inconvenient degree of uncertainty, both as to exploration and later, perhaps, to moving oil out.

Then there is another problem on which not very much

has been said, *i.e.* radio communication, which in those latitudes is again rather an uncertain factor. I am not in a position to discuss the physical reasons, but it is a fact that radio silence for periods of hours or up to as much as 11 days is well known in Resolute, which will interfere not only with contact between the base and the out-stations but also with navigational aids. This sort of thing, plus very bad flying weather, will in the long run lead to quite a casualty rate, or a serious danger of it, unless some novel method of navigation is developed.

Leaving that side of things, one of the most entertaining aspects of this Arctic area from the geological point of view is the large gypsum plugs. Mr Bryce Cameron referred to them as salt plugs, and I would be interested to know whether he believes they are salt plugs at depth. They may very well be, but so far there has been remarkably little evidence of sodium chloride in them. As far as I know, the evidence is all of gypsum and anhydrites. Aero-magnetic traverses have crossed them, and a sort of annular anomaly is found, a " high " over the edge of the plug, which is presumably related to the turn-ups of igneous rocks on the periphery of the plug. But it would be very interesting indeed if a gravity survey could be run across one of these plugs to find whether there is a negative anomaly which indicates salt at depth. A lot of weight is being attached to these plugs as oil prospects, and it is quite important to examine the mechanism by which they reach the surface.

A. Bryce Cameron: I agree that the ice conditions can be quite formidable; wind and weather do alter the approaches, but along Parry Sound, as far as Resolute Bay, ships have been coming in every year since the shipment of cargoes was started after the war, when weather stations were established. But day to day conditions do vary according to wind, and other factors.

I myself have experienced four days of radio blackout when, though not knowing what the weather was like at Resolute Bay, we were held up at Cambridge Bay and were not able to proceed further. From Cambridge Bay to Resolute Bay is some 500 miles, or 1000 miles there and back, and our small aeroplane had a range of 800 miles, which would have meant rather a long walk if we had come down. But these things are not occurring all the time.

I am afraid I used the words " salt plugs " rather loosely. A piercement dome is what I really meant to say. I too have no evidence of salt, *i.e.* sodium chloride, and what Dr Kent suggests about a gravity survey might be most interesting indeed.

Peter Bawden (Peter Bawden Drilling Ltd): We have been drilling in the Western Arctic for the past two years and the problems which have been emphasized in the question period are most important ones in any such remote area—those of supply, re-supply, and communications. As far as the performance of drilling operations in the North is concerned, we find that, with careful planning, problems are not much greater than operating in parts of Northern Alberta and British Columbia, as Mr Cameron has suggested. Certain precautions must be taken, however, when working in very cold areas, more than are necessary in more southerly areas of Canada.

From a transportation point of view in operating in these places, an effective airlift is almost a necessity. Despite the very bad flying conditions encountered in our operations in the Western Arctic, we have never failed to get our aircraft, a DC-3, to the location every time we have attempted it, and the aircraft has never been held up by weather for more than a day or two. In the Arctic Islands weather is somewhat more difficult, and our study indicates that at no time would we ever be held up for more than ten days.

On the matter of aircraft radio facilities, I would say that navigating the aircraft has never presented any serious difficulties. It is a difficult flying area, however, and experienced pilots are essential. There are ADF beacons in the area, and when planes depart from one point the radio compass can be set on the next. The beacons are higher powered in that area, so they are effective over a great distance. As has been pointed out, atmospheric conditions do occasionally hamper their successful operation.

The Dew Line, which is on the northern edge of the continent, has excellent communications, but these are only available to defence people who are working on the Dew Line. The Canadian Government has not so far made any large contribution towards good communications for civilians. We feel that their equipment is antiquated and outdated, and when operators such as Lobitos go into this area they should have no problem if they purchase good modern radio equipment. Last summer we set up a small radio set weighing about 60 lb in a tent, with a 60-mph wind blowing, and successfully spoke to our office in Edmonton over a 1500-mile distance. We also talked 1000 miles to the south and west and had a very excellent conversation with the crews on our other Arctic rig. Communication will certainly improve as activity increases.

As far as drilling in the Islands is concerned, we foresee no major problems, either in the drilling or re-supply operations, or subsequent completion of oil wells.

To comment on Mr Cameron's paper, having visited the area personally and having had a great interest in Arctic areas and operations for a number of years, I feel that he has been conservative and has given a very fair and reasonable presentation of the facts and conditions in Canada's Arctic Islands.

E. Cooper-Scott: I think that members might be interested in one case of seepage I know of in permafrost conditions in the North West Territories. It occurs at Rond Lake in outcropping Cretaceous age rocks and a profile of shallow wells was drilled to examine it. It was found that the Cretaceous rocks were of very small surface extent and were in fact an outlier resting on Devonian rocks, and thus there was a very big unconformity between the two.

There is no oil impregnation in the Devonian; therefore it would seem that the Pleistocene ice age, which eroded all but this small outlier of the Cretaceous, froze its oil content and trapped it *in situ* from that time up to the present day.

Now each summer the sun's heat melts a little of the Pleistocene ice and releases a little of the oil content.

W. M. Booth (Commonwealth Drilling Co. Ltd): Transportation of drilling equipment around the islands is an interesting problem that we have looked into. I had the pleasure of making two trips with Mr Cameron to the islands last summer, in conjunction with our transport superintendent, who has appraised the problem of moving the equipment on the islands, as well as making the initial beach landing and move-in. We think at present that on the initial venture into the islands we should use Athey wagons towed by Caterpillar tractors for transportation of the drilling equipment. During two months of the summer, the ground thaws to a depth of 2 or 3 feet and there are quite a few soft areas where

this type of equipment would be required. During the other ten months, the ground is frozen and soft areas are not a problem. Drifting snow may become a problem at that time, but here again the Athey wagon should be suitable.

There is an estimated 1000 to 1200 feet of permafrost which may pose some problems from the drilling standpoint. There is some thought that it may be necessary to drill this permafrost with a drilling fluid at a temperature below the freezing point of the formation to prevent thawing of the permafrost. This could be accomplished by use of cold brine solutions or even diesel fuel. Several cementing companies have made investigations of the problem of securing a good cement job on the surface casing to ensure that it is well stabilized and is well anchored for blowout prevention. It appears that this can be accomplished without much difficulty.

From a personal standpoint, we visualize two crews on a 12-hour basis operating the rig. These crews would work in the area possibly four weeks, and would then be flown out for a two-week rest period in their home vicinity. We think that with proper provision for good food, recreation, and mail deliveries, crew morale would be no problem, even in periods of winter operation where total darkness exists for 24 hours. In contrast to this, the summer provides ideal working conditions, with 24 hours of daylight.

R. Sparrow (Peter Bawden Drilling Ltd): I would like to mention two points which we have found of interest. We have drilled two wells in the MacKenzie Delta area of the North West Territories, the last one being approximately 75 miles north of the Arctic Circle (Latitude 67° 35′ N). In this last well, we were advised by the Canadian Government that we could anticipate 600 to 800 feet of permafrost. With the experience that we had gained in our first well, where we had encountered about 500 feet of permafrost, plus studying the work that the U.S. Navy had done on their petroleum reserve in Alaska, we found that we were able to drill the first 60 feet of clay and overburden with a gel water slurry, without having any freezing problems. We then cemented 20-inch conductor casing at that depth without having any major cementing problems. We did warm our cement slurry and add calcium chloride to set the cement. The remainder of the surface hole we drilled as we would drill anywhere in Canada, and cemented the surface casing with normal cementing practices.

We found that during the extremes of winter temperatures, particularly below −40° F, steel became very brittle and would shatter like glass under severe shock loading. This was a phenomenon that we had possibly expected, but we were not quite prepared for the severity with which it affected some of our equipment. Mr Booth has mentioned Athey wagons, which we operated throughout the winter. The hitches on the Athey wagons were made of 20-inch square sections of steel, and some of those broke right through, because of shock loading during severe temperature conditions.

— **Guest** (F. Perkins Ltd): When Mr Cameron showed the area enclosed by an isosceles triangle I found it a little difficult to visualize what distances we are looking at over all the islands. What would be the dimensions of that triangle? Secondly, are similar activities going on in the latitudes in the northern part of Alaska, Greenland, or is anything going on in Russia in these latitudes and on a similar sort of scale?

A. Bryce Cameron: The southern limb of that triangle must be about 800 miles long, and the northern limb, going up from the apex of the triangle to the top of Ellesmere Island, 800 miles as well. The base, along the Arctic Ocean, would be a bit more.

Regarding similar operations in Greenland, I would say that none are going on and, moreover, we do not know of any suitable sedimentary conditions in Greenland to visualize anything happening there. On the Arctic shore of Alaska there are oil and gas wells on a naval reserve. They were discovered during and after the second world war, from 1944 to 1953, during which time the Americans sent large task forces with many drilling rigs and seismic operators. Photo studies were also made, quite a number of wells were drilled, and oil and gas were found on the northern shores of Alaska. In Southern Alaska, also, oil has more recently been found, but that is outside the Arctic Ocean.

Concerning Russia, I am afraid I have not recently refreshed my memory, but I seem to recall that considerable activity is going on in Siberia and other areas fronting the Arctic Ocean.

Dr L. V. Illing: In connexion with Mr Cameron's last remarks about Russia, the symposium on Arctic Geology organized and sponsored by the Alberta Society of Petroleum Geologists in January 1960 has just been published by the Toronto University Press. In it there will be found extensive Russian contributions (in English) and maps on the Soviet Arctic Regions, contributions on the Canadian Arctic, Danish contributions on Greenland, discussions of Spitzbergen and Iceland, and also American contributions on Alaska.

In connexion with the geology of the Canadian Arctic Islands, I think a tribute should be paid to the Geological Survey of Canada, whose officers have done and are doing a magnificent job there. The situation is entirely different from that in the petroleum provinces of Western Canada, where, since Leduc was discovered in 1947, the petroleum industry has poured in geologists by the hundreds. With very limited manpower, the Survey has been hard put to it to keep up with the developments resulting from oil and gas exploration, and there is a tremendous amount of detailed geological information, both surface and subsurface, in industry files with which the Survey is not and cannot be familiar.

In the case of the Arctic Islands, starting in 1954 or thereabouts, the Survey has gone in and has pioneered. The interest of industry came later, and was in fact founded on Survey reports. Most of the geological knowledge that we have now, particularly the regional picture which is so important at this early stage in exploration, is, as I am sure Mr Cameron would agree, based on the work of the Geological Survey of Canada.

A. Bryce Cameron: I would like to give my full support to the view that we owe much to the Geological Survey of Canada. They have done an enormous amount of work up there. If it were not for that work, we would possibly not have been attracted to the area at all and would certainly not have progressed as far as we believe we have. They have done a magnificent job.

The President then called for a vote of thanks to the author, which was accorded with acclamation.

WRITTEN DISCUSSION

Dr G. D. Hobson (Imperial College): It would appear that production from the wells for only part of each year is visualized. Otherwise, large storage facilities would have to be constructed locally, as well as those suggested for construction in Greenland. Production for only a few months each year raises a number of problems. The overall producing life of a field might be substantially longer than that of an equivalent field produced continuously. Consequently, is a period of 21 years reasonable for the lease? The income to repay the capital invested would be obtained more slowly than usual, reducing the present-day value of the recoverable oil. To offset these factors there might be justification in increasing the number of wells beyond the minimum which might be appropriate for a similar field in a better climatic zone. The producing rates at abandonment would probably have to be higher, and the probable long producing life would call for greater durability in well and other equipment than elsewhere. There might, however, be some advantages in intermittent production, provided that excessively high well rates were not used during the producing periods, although this might not be the case in all types of oil accumulation. Development and operating policies would have to take note of these considerations, and the final legislation should not ignore them if the search for oil in these remote areas is to be encouraged.

B. H. J. Thoms (Dept of Northern Affairs and National Resources, Canada): One of the things which does not seem to have been made apparent in the paper is that most of the land held under exploratory permit in the islands, where coasts or part of coasts become seasonally ice free, is nearer than 40 miles to navigable tide water. This means that no long-distance crude oil pipelines will be required to take any oil that may be found to a tanker loading point.

Very large recoverable reserves of crude oil will have to be found before the capital outlay required for the building of nuclear-fuelled submersible tankers could be justified. These vessels have already reached the design study stage both in the U.K. and in the U.S.A. and such information as has been released indicates that these vessels are technically practicable. Until sufficient recoverable reserves are found to make economic the building of a submersible tanker fleet, it should not be overlooked that seasonal deliveries of Arctic Island crude could be made on a spot basis to markets in North-west Europe and on the Atlantic seaboard of Canada. The advantage of this is obvious, as some income may be expected to be obtained during the first open navigation season after oil is discovered. The possibility of some immediate revenue is not generally the case when a land-locked discovery of oil is made.

It might be mentioned that in August 1960 a master mariner from Copenhagen, with great experience in Arctic navigation, accompanied one of the parties visiting the islands. He expressed the opinion that for conventional ships seasonal navigation in a normal year might be expected to extend over a period of four months, though an accompanying ice-breaker would be required during the build-up of new ice after it had reached a certain thickness. The beaches examined showed amply deep water near the shore, and navigation generally, it appeared, would be easier than on the Antarctic and East Greenland coasts.

It is well known that the build up of new ice is much more gradual than its fairly rapid melting (Fig 3), and for this reason it is unlikely that surface navigation could be opened earlier in the season than early August. This is the time that the annual re-supply convoy for the existing settlements now arrives. During the period of ice build-up one ice-breaker could accompany several tankers.

THE FLOW OF OIL AND GAS MIXTURES IN WELLS AND PIPELINES: SOME USEFUL CORRELATIONS *

By W. J. BAKER † (Associate Member) and K. R. KEEP †

SUMMARY

Calculations relating to the flow of oil and gas mixtures in oil wells and pipelines involve the integrals of (vdp) and (ρdp). General correlations have been obtained from 22 Middle East crudes which enable these integrals to be evaluated for any pressure changes occurring in a well or pipeline. It is estimated that the correlations are about 5 to 10 per cent accurate for oils with stock tank specific gravities in the range 0·80 to 0·92 (45° to 22° API). A correlation of gas–oil ratio with saturation pressure, similar to that of Standing,[1] has also been obtained.

These correlations simplify the design of oil well flow-strings and flowlines to the extent that it becomes no more difficult than designing for single phase flow. At the same time it is only necessary to know the saturation pressure and stock tank gravity of the oil in order to carry out flow calculations within reasonable limits of accuracy.

The method of plotting the integrals, in which pressures are expressed as fractions of the saturation pressure, results in a single curve covering the whole range in saturation pressures. This is of particular value in that it means that it is only necessary to establish the relationship at one saturation pressure. The use of the curves can thus be extended to include the case of a well producing at higher than the original gas–oil ratio, or by gas lift, by using an equivalent saturation pressure obtained from the correlation of gas–oil ratio and saturation pressure. A condition that must be satisfied in using the correlations is that the oil and gas flow as an intimate mixture and no separation of the two phases occurs.

NOMENCLATURE

p = pressure, psia
p_s = saturation pressure of the oil and gas mixture, psia
v = specific volume of the oil and gas mixture, cu ft/lb
v_s = specific volume of the oil and gas mixture at p_s, cu ft/lb
ρ = density of the oil and gas mixture at p, lb/cu ft
ρ_o = oil density, lb/cu ft
ρ_g = gas density, lb/cu ft
R = gas–oil ratio, vol of gas at average flowline temperature/vol of stock tank oil at 60° F
h = height above a datum level, ft
u = velocity of the fluid, ft/sec
w = mass flowrate, lb/sec
Q = flow rate, bd
g = 32 ft/sec/sec
L = length of the pipeline, ft
D = internal diameter of the pipeline, or casing, ft
d = external diameter of the tubing, ft
F = friction factor
μ = viscosity of a liquid, fps units
W_e = external work done by or done on the fluid, ft lb
W_l = energy loss by friction and gas slippage, ft lb
S = slippage loss, ft
G = specific gravity of the oil, 60° F/60° F
T = temperature, ° F
b = velocity of gas slip, ft/sec

$$I(p) = 144\int_{p_s}^{p} \rho dp$$

$$I(v) = 144\int_{p_s}^{p} v dp$$

$$I(v^2) = 144\int_{p_s}^{p} v^2 dp$$

$$K = \frac{64Fw^2}{g\pi^2D^5}$$

Subscripts 1 and 2 denote the initial and final values of a quantity.

INTRODUCTION

THE production of oil from reservoirs through casing or tubing and its transportation through surface pipelines to production centres involves calculations of pressure changes due to the flow of oil and gas mixtures of varying densities. These become especially important in typically large fields of the Middle East, where highly productive wells on wide spacings are connected to gathering centres by long flowlines. Another important application is in the flow of oil and gas mixtures from offshore wells through long pipelines to separator stations on land.

Calculating techniques for obtaining pressure losses in pipes as a function of flow rate have been described by a number of authors.[2–5] The methods that have been developed are very similar in principle and are based, in effect, on various ways of integrating the differential energy equation for a unit mass of a gas–oil mixture. The resulting formulæ involve $\int vdp$ for describing vertical flow in oil wells and $\int \rho dp$ for horizontal flow in surface pipelines.

The normal and most direct way of evaluating the integrals is from $(p$–v–$T)$ measurements on bottom hole samples of the crude oil. The measurements would have to be repeated on a range of samples if there was a significant variation in saturation pressure in different parts of a reservoir, and also to cover any changes in saturation pressure with production. Similarly, another series of measurements would have to be made on, say, first stage separator samples if it was proposed to flow the separated oil for any distance through a pipeline.

* MS received 8 August 1960.

† The British Petroleum Co. Ltd.

The correlations presented in this paper, which are based on (p–v–T) measurements on 22 Middle East crudes, make it possible to evaluate the integrals with an accuracy of 5 to 10 per cent without having recourse to a large amount of laboratory work. Essentially the correlations have been obtained by plotting the integrals divided by the saturation pressure against pressure expressed as a fraction of the saturation pressure. This results in a single curve for a particular oil which applies to the whole range of saturation pressures. Thus when (p–v–T) work is carried out on crude oil from a newly discovered reservoir it is only necessary to make measurements at one saturation pressure to cover all possible cases of flow.

The saturation pressure required when using the correlations is that of the flowing oil and gas mixture which may be the same or may differ from the original saturation pressure, depending on the circumstances. For example, under solution gas drive conditions the saturation pressure varies throughout a reservoir and the produced gas–oil ratio increases with production. Changes in well potentials with production for such cases can be calculated using an increasing saturation pressure. The latter can be estimated from a gas–oil ratio v. saturation pressure correlation presented in a later section concerned with gas lift calculations.

It is implicitly assumed when calculating flowing pressures by means of the correlations that the gas liberated from the oil by a reduction in pressure is uniformly dispersed throughout the oil, and that this gas does not separate out from the oil on account of its density difference. Thus the correlations do not apply to the situation, called gas slippage, where small gas bubbles rise through the flowing oil, and they also do not apply to slug-flow in which large scale separation of the oil and gas occurs and slugs of oil and gas flow separately.

THEORY OF THE FLOW OF OIL AND GAS MIXTURES IN PIPES

The energy balance for one pound of fluid in a pipe can be written as

$$\underset{(a)}{-144\,vdp} = \underset{(b)}{dh} + \underset{(c)}{d(u^2/2g)} + \underset{(d)}{W_i} \pm \underset{(e)}{W_e} \quad (1)$$

where the various terms, all in ft lb, are:

(a) energy of expansion of the fluids;
(b) potential energy change;
(c) change in kinetic energy;
(d) loss of energy by friction, etc.;
(e) external work.

For the cases considered in this paper the kinetic energy term is negligible and the external work is zero.

The integration of equation (1) to determine pressure losses in pipes takes various forms, depending on the relative importance of the potential energy term and the energy loss in the pipe. It is usual to distinguish two cases, namely,

(1) horizontal flow in pipes;
(2) vertical flow in wells.

In the first case, energy loss from friction is the dominant term, and small changes in the elevations of the ends of the line causing potential energy changes are applied as corrections. In the second case, potential energy changes are large and energy losses are treated as corrections.

Horizontal Flow in Pipes

In horizontal flow equation (1) becomes

$$-144\,vdp = W_i = \frac{64Fw^2dL}{g\pi^2D^5\rho^2}$$

but

$$\rho = \frac{1}{v}$$

$$\therefore \quad -144\,\rho dp = \frac{64Fw^2}{g\pi^2D^5}\,.\,dL$$

from which

$$144\int_{p_1}^{p_2} \rho dp = \frac{64Fw^2L}{g\pi^2D^5} \quad . \quad . \quad (2)$$

where $p_2 < p_1$. When $p_1 = p_s$, the saturation pressure the integral multiplied by 144 will be denoted by $I(\rho_2)$.

The evaluation of the friction factor F for a two-phase mixture of oil and gas is a problem for which no general solution has yet been found. A natural first approach to this problem is to treat it in the same way as for single-phase flow where the friction factor is correlated with the Reynolds Number, $D\rho u/\mu$.[6] The product ρu is constant for a two-phase mixture of oil and gas, and can therefore conveniently be evaluated from the density of the single-phase saturated oil and its equivalent velocity in the pipe; there is no means of evaluating the viscosity μ of the mixture. Yocum[7] found that good agreement with experimental data was obtained if the liquid phase viscosity was used to determine the Reynolds Number and the friction factor obtained from the standard correlations for single-phase flow. Baxendale[4] ignored viscosity and obtained a good correlation of F against $D\rho u$ for La Paz crude over rather a limited range of pressure and specific volume. It is interesting to note that the values of friction factor which he obtained at the higher rates of flow fall in the comparatively narrow range of 0·002 to 0·0025. This agrees with our own experience with Middle East crudes and also, incidentally, with the friction factors for single-phase flow at high Reynolds Numbers. It would therefore appear fairly safe to use a friction factor of this order except in the case of very viscous crudes or very low rates of flow. Furthermore, equation (2) shows that the flow

rate varies inversely as the square root of the friction factor, and can therefore be estimated with an accuracy of ±5 per cent if a mean value of the friction factor of, say, 0·0023 is used.

Thus in calculations of oil and gas mixtures in horizontal pipes the chief problem is to evaluate $I(\rho)$. The correlations in this paper enable this integral to be determined from the saturation pressure of the oil and gas mixture and the stock tank specific gravity of the degassed oil.

In the case of an inclined pipeline the static pressure drop (or gain) may be calculated from the mean density of the oil and gas mixture and the difference in elevations between the ends of the line. The mean density is obtained, as a first approximation, by dividing the value of $I(\rho)$ by the frictional pressure drop, as calculated for a horizontal line of the same length. This method is sufficiently accurate if the angle of inclination of the pipe is small and the static head a small proportion of the total pressure drop, as is usually the case. If the angle of inclination is very great the problems may be treated in the same way as for a well using a modification of equation (4).

It is assumed in problems of the flow of gas–oil mixtures that there is equilibrium between the two phases at all pressures. This assumption is considered to be quite valid under conditions of turbulent flow and falling pressure, but there is some doubt as to whether it is altogether true in the case of rising pressure, such as occurs in flow down a steep gradient, because it has been observed that gas comes out of solution much more readily than it goes into solution. This affects the calculation of static pressure differences in an inclined flowline, where the gradients may be both positive and negative, to the extent that any theoretical gain in pressure on the down grades will probably not be attained in practice.

A further point of great practical importance is that a sharp change of gradient from positive to negative is liable to cause gas locking, due to gas accumulating at the highest point, and should therefore always be avoided by suitably grading the line.

Vertical Flow in Wells

When friction and other energy losses are negligible, the integration of equation (1) gives directly the height h in feet to which one pound of the mixture will be lifted by a pressure drop $(p_1 - p_2)$, as follows:

$$144 \int_{p_1}^{p_2} v\,dp = h \quad . \quad . \quad . \quad (3)$$

When $p_1 = p_s$, the integral, multiplied by 144, will be denoted by $I(v_2)$. As with the case of horizontal flow, correlations in this paper will enable this integral to be determined from the saturation pressure and the stock tank specific gravity of the oil.

At flow rates where friction is appreciable, equation (1) becomes

$$-144\,v\,dp = dh + \frac{64Fw^2}{g\pi^2 D^5 \rho^2}\,dh$$

which can be written in the form

$$-144\,v\,dp = v\,dh\,(1 + Kv^2)$$

where $K = \dfrac{64Fw^2}{g\pi^2 D^5}$ and $v = \dfrac{1}{\rho}$

Hence

$$h = 144 \int_{p_1}^{p_2} \frac{v\,dp}{(1 + Kv^2)} \quad . \quad . \quad . \quad (4)$$

In the majority of cases $Kv^2 \ll 1$ so the denominator of the integral can be expanded by the binomial series and, neglecting terms in $(Kv^2)^2$ and higher powers, the formula for h becomes

$$h = 144 \int_{p_1}^{p_2} v\,dp - 144K \int_{p_1}^{p_2} v^3\,dp \quad . \quad (5)$$

When $p_1 = p_s$ this becomes

$$h = I(v_2) - KI(v_2{}^3) \quad . \quad . \quad . \quad (6)$$

Comparing this equation with equation (2), it is clear that friction reduces the lift h by $KI(v^3)$. This is easily changed to a loss of pressure, as will be shown later in an example. A correlation has also been obtained for $I(v^3)$ by expressing pressures as fractions of the saturation pressure, as in the correlations for $I(\rho)$ and $I(v)$.

Equation (4) can be applied to the case of an inclined pipeline if K is multiplied by cosec θ, where θ is the angle of inclination of the line to the horizontal.

Flow in an Annulus

The above equations apply to flow in tubing or casing where the cross-section is circular. Wells are, however, frequently produced through the annulus between the tubing and the casing, and in this case the same equations may be used, though with a different value of K. The value of K for an annulus is given by the equation:

$$K = \frac{64Fw^2}{g\pi^2(D^2 - d^2)^2(D - d)}$$

Gas Slippage

It should be noted that in the vertical flow of an oil–gas mixture there is always a further loss of energy due to slippage of the gas through the oil due to the difference in density of the two phases. Slippage becomes the predominant source of energy loss at very low rates of flow, such as would not normally occur in a properly designed flow string, but it is always present to some degree, and may be appreciable, even at high rates of flow, if the gas–oil

ratio of the flowing mixture is high. A theoretical treatment of the slippage problem has been given by May and Laird,[2] but this is not easily applied to practical calculations. The following empirical equation, which was evolved from a careful analysis of flowing conditions in two of the Persian oilfields, is of interest as an indication of the sort of way slippage loss varies with flow rate, etc., but it is not claimed to be of universal application.

$$S = 990\ (b/Q)^{0.85} D^{1.4} p_s (v - v_s)$$

where S = slippage loss, ft;
v = specific volume of mixture at flowhead pressure, cu ft/lb.

The velocity of slip, b, is the velocity of the gas bubbles relative to the oil and tends to decrease as the specific volume of the mixture increases, and is thought ultimately to disappear at some stage where a stable foam is formed. It was found, however, that a constant value of 0·5 ft/sec could be used with reasonable accuracy up to a ratio of $v/v_s = 5$.

The Effect of Temperature

The main effect of temperature is on the energy of expansion of the oil–gas mixture, and, in the case of isothermal flow, it is taken care of by using a value of the saturation pressure corrected to the temperature of flow. The flowing temperature of a gas–oil mixture under adiabatic conditions falls as the mixture expands, but in practice it is also affected, usually to a much greater extent, by heat transfer with its environment. Thus the geothermal conditions influence the flowing temperature in a well as do the meteorological conditions in the case of a surface pipeline.

It is extremely difficult to predict variations in flowing temperatures with any accuracy, but fortunately their effect is of relatively secondary importance. It is therefore sufficiently accurate for most purposes to treat the flow as isothermal, using a best estimate of the mean temperature of flow. If, however, a greater degree of accuracy is required and the flowing temperature gradient is known it is possible to construct a p–v or p–ρ curve corresponding to this gradient provided the experimental figures cover the necessary temperature range. These curves can then be used to give more exact values of the integrals.

EVALUATION OF $I(\rho)$ AND $I(v)$

The correlations are based on Middle East crudes with saturation pressures ranging from 490 to 4390 psia and stock tank oil specific gravities from 0·811 to 0·924. The specific gravities of the stock tank oils used in the correlations were all measured at 60° F, but different gas separation conditions had been used for stabilizing the oils. Either differential gas liberation or several stages of separation were used, and the resulting specific gravities would depend on the process; differential liberation would give the lowest specific gravity. However, it is unlikely that the different processes would vary the specific gravity by more than about 0·005, which is small compared with average deviations from the correlations due to other causes.

For each of the crude oils used in correlations, $I(\rho)$ and $I(v)$ were evaluated numerically from a p–v curve. The temperatures used in measuring the curves varied from 95° to 200° F. The method of deriving the correlations was very similar, and the process for the $I(\rho)$ correlation is described for illustration.

$I(\rho)$ CORRELATION

When values of $I(\rho)$ were plotted against p for various oils it was apparent that the curves for

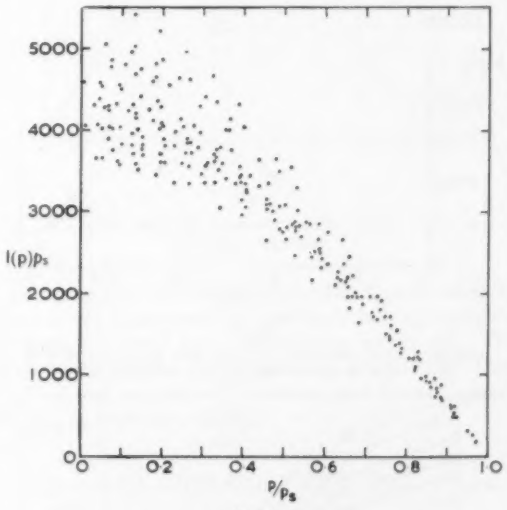

FIG 1
CORRELATION BETWEEN $I(p)/p_s$ AND p/p_s (UNCORRECTED)

different crudes were of the same shape, and that values of $I(\rho)$ at any particular fractional value of p_s were approximately proportional to the saturation pressure. This led to the results being plotted in the form $I(\rho)/p_s$ against p/p_s. The resulting distribution can be seen in Fig 1. It was noticed from this that crude oils with higher stock tank specific gravities, G, tended to have larger values of the integral at any particular value of p/p_s. This is shown clearly in Fig 2, where values of $I(\rho)/p_s$ at $p/p_s = 0{\cdot}25$ for the different crudes have been plotted against G. The straight line is the least squares fit.

Correction factors taken from Fig 2 were used to "reduce" all the points of Fig 1 to a common G of

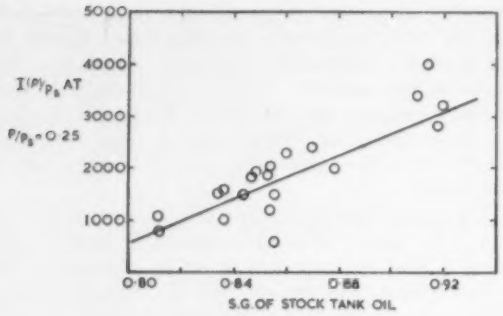

FIG 2

CORRELATION BETWEEN I(p)/p_s AT $p/p_s = 0{\cdot}25$ AND STOCK TANK OIL SPECIFIC GRAVITY

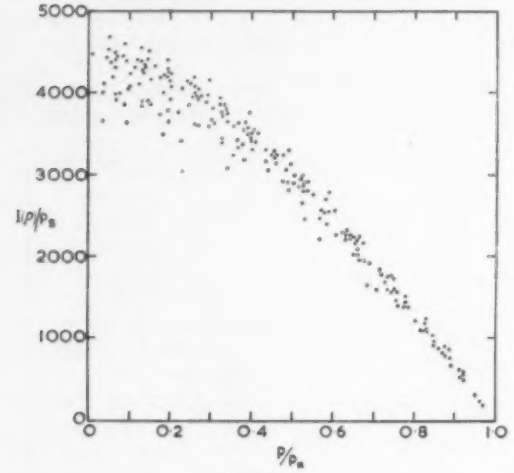

FIG 3

CORRELATION BETWEEN I(p)/p_s AND p/p_s FOR STOCK TANK OIL SPECIFIC GRAVITY = 0·86 AT 60° F

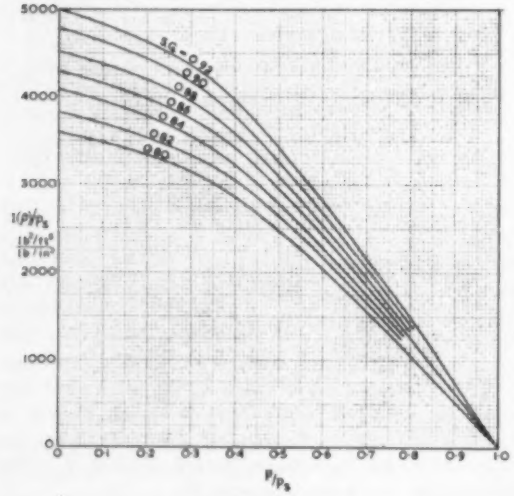

FIG 4

I(p)/p_s AS A FUNCTION OF PRESSURE AND STOCK TANK OIL SPECIFIC GRAVITY

0·86. This implicitly assumes that the curves of $I(\rho)/p_s$ against p/p_s for the different crudes are the same shape. The distribution of points obtained in this way is shown in Fig 3. Figs 2 and 3 were then used to prepare general correlations with G as parameter by first drawing an estimated mean curve through the points on Fig 3 which was taken to be the correlation for $G = 0{\cdot}86$. Curves for other values

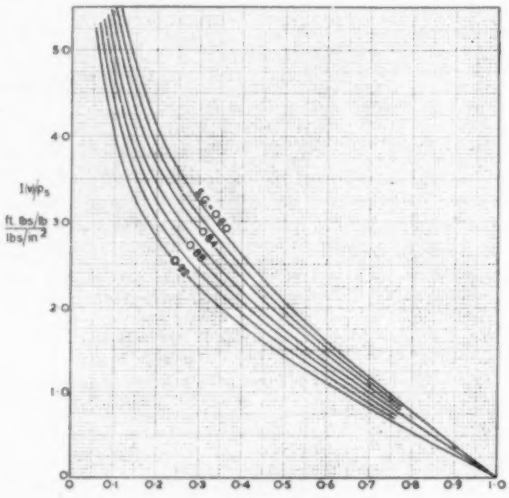

FIG 5

I(v)/p_s AS A FUNCTION OF PRESSURE AND STOCK TANK OIL SPECIFIC GRAVITY

of G were then obtained by scaling this curve with factors obtained from Fig 2.

The general curves constructed by this method for stock tank oil specific gravities in steps of 0·02 in the range 0·80 to 0·92 are shown in Fig 4. The correlation for $I(v)$ was obtained in exactly the same way and can be seen in Fig 5.

An important feature of both the $I(\rho)$ and $I(v)$ correlation is that they seem to be independent of temperature. As mentioned earlier, the p–v data used in the correlations were measured at temperatures varying from 95° to 200° F; in fact, the appropriate reservoir temperature. For any particular oil the effect of an increase in temperature on the integrals is approximately compensated by an equivalent change in the saturation pressure. An example illustrating the use of the correlations is given in the Appendix.

ACCURACY OF THE CORRELATIONS

The accuracy of the $I(\rho)$ correlation is shown by the scatter of points from the straight line in Fig 2. In the case of both the $I(\rho)$ and the $I(v)$ correlations the standard deviation at $p/p_s = 0{\cdot}25$ is approximately

5 per cent, which, by inspection of Fig 3, is approximately the spread at all values of p/p_s. The exception to this is in the $I(v)$ correlation at pressures below about $p/p_s = 0{\cdot}1$, where the accuracy deteriorates, and for this reason it is not recommended that this correlation should be used below about $p/p_s = 0{\cdot}1$.

The residual scatter after correcting for stock tank oil specific gravity may be due to a large number of factors, such as gas gravity, the presence of non-hydrocarbon gases, and so on. The introduction of these secondary effects was not considered worthwhile in view of the additional complications involved and because the correlations are considered to be very satisfactory as they stand.

CORRELATIONS FOR CALCULATING FRICTION LOSSES IN WELLS

Two further correlations have been derived which are useful for calculating the loss in pressure or lift due to friction. The first is a correlation for obtaining $I(v^3)$, which is defined in equations (5) and (6), and the second is a correlation of density of oil and gas mixtures with saturation pressure. The methods of deriving the correlations were very similar to those used for the $I(\rho)$ and $I(v)$ correlations.

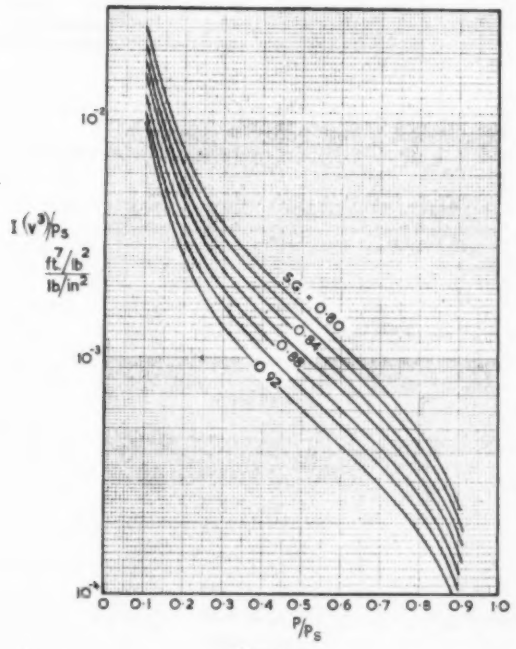

FIG 6

FRICTION LOSS: $I(v^3)/p_s$ AS A FUNCTION OF PRESSURE AND STOCK TANK OIL SPECIFIC GRAVITY

The correlations for $I(v^3)$ and for ρ are shown in Figs 6 and 7 respectively. As with the other correlations, a general set of curves with stock tank oil specific gravity as parameter have been obtained by expressing pressures as fractions of the saturation pressure. The example given in the Appendix illustrates the uses of these correlations in determining friction losses in wells.

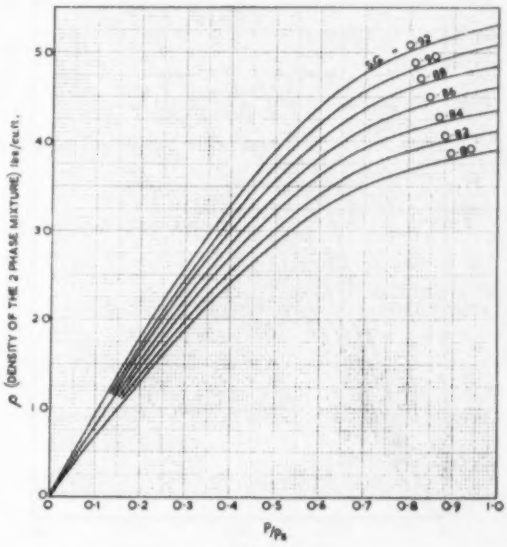

FIG 7

ρ AS A FUNCTION OF PRESSURE AND STOCK TANK OIL SPECIFIC GRAVITY

In using the $I(v^3)$ correlation, due regard must be given to the approximation used in obtaining equation (5) from the exact form given by equation (4). The binomial expansion of equation (4) necessitated that $(Kv^2) \ll 1$ of equation (5) is to be used for estimating the loss in head by friction.

GAS LIFT CALCULATIONS

In gas lift calculations the correlations can be used to determine pressure changes if at first the saturation pressure of the oil and injected gas can be estimated. This can be done from published correlations of saturation pressure against gas–oil ratio.[1,8] A correlation derived from Middle East crudes which may be used for this purpose can be seen in Fig 8. This graph shows saturation pressure as a function of dissolved gas–oil ratio and stock tank oil specific gravity. It is also expected that the correlation should depend on gas gravity and temperature, but it was not possible to determine the effect of these from the experimental results. Probably because of the neglect of the latter two factors, the correlation is only about 20–30 per cent accurate for predicting saturation pressures from known gas–oil ratios below 3000 psig. Above this pressure the curves are shown

as broken lines because of the very limited amount of information available on high saturation pressure oils.

It must be emphasized that the correlation has been included because it can be used for predicting changes in saturation pressure for changes in gas–oil ratio with sufficient precision for pipeline calculations. It is not recommended that it should be used for determining saturation pressures corresponding to known gas–oil ratios, or vice versa.

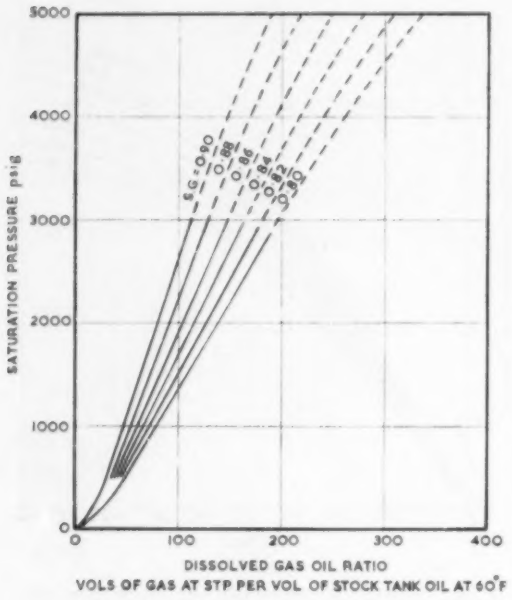

FIG 8

CORRELATION BETWEEN SATURATION PRESSURE AND DISSOLVED GAS–OIL RATIO

CONCLUSIONS

The correlations and methods of calculation presented in this paper provide a quick and easy means of performing flow calculations for oil–gas mixtures covering the whole range of possible conditions in an oilfield installation. Thus, flow up a well at normal and higher than normal gas–oil ratios, flow from a well head to a separator, and flow from a separator to a gathering centre can all be calculated with an accuracy which is sufficient for most purposes without having recourse to a large programme of p–v–T and other laboratory determinations.

The design of well flowstrings and surface flowlines involves the selection of a suitable pipe size from a comparatively limited range of available sizes which differ very markedly from each other in flow capacity. Great accuracy is therefore not required for design calculations, and the correlations are ideal for this purpose.

ACKNOWLEDGMENTS

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APPENDIX

An example is worked out below which shows how the correlations are used in a typical problem of determining the wellhead and flowline pressures for given conditions. It will be assumed that the saturation pressure of the oil is constant, *i.e.* there is no difference in the average temperature of the flowline and the well.

Given

Saturation pressure	= 1500 psia
Sp gr of stock tank oil	= 0·83
Depth of formation	= 2500 ft below surface
Bottom hole pressure	= 1280 psia
Diameter of tubing	= 4 inches
Gas gravity	= 0·8
Production rate	= 5000 bd
Length of surface flowline	= 1 mile
Diameter of flowline	= 4 inches
F for both tubing and flowline	= 0·0025
Gas–oil ratio	= 95 vol/vol

(*a*) *Well Head Pressure*

(i) *Neglecting Friction.* From equation (3)

$$144 \int_{p_1}^{p_2} v\,dp/p_s = h/p_s$$

from which $I(v_2)/p_s - I(v_1)/P_s = h/p_s$

But $p/p_s = \dfrac{1280}{1500} = 0{\cdot}85$

$\therefore \quad I(v_1)/p_s = 0{\cdot}55$ (from Fig 5)

$\therefore \quad I(v_2)/p_s = 0{\cdot}55 + \dfrac{2500}{1500}$

$= 2{\cdot}22$

From Fig 5 $\quad p_2/p_s = 0{\cdot}44$

$\therefore \quad p_2 = 660$

The well head pressure = 660 psia

(ii) *Friction Loss.* From equation (5) the loss in lift Δh due to friction can be written in the form

$$\frac{\Delta h}{p_s} = \frac{K}{p_s}\left[\, I(v_2{}^3) - I(v_1{}^3) \,\right]$$

(The value of Kv^3 is approximately 6×10^{-3}, so the approximate flow formula as given in equation (5) can be used rather than the exact form in equation (4)).

From the correlation in Fig 6

at bottom hole $p/p_s = 0{\cdot}85$

$\therefore \quad I(v_1^2)/p_s = 2{\cdot}9 \times 10^{-4}$

at surface $p/p_s = 0{\cdot}44$

$\therefore \quad I(v_2^2)/p_s = 16{\cdot}5 \times 10^{-4}$

The relation between mass flow rate w in lb/sec and the volume flow Q in bd is as follows

$$w = Q\,\frac{(\rho_s + R\rho_g) \times 5{\cdot}61}{24 \times 60 \times 60}$$

from which

$$w = 18{\cdot}6 \text{ lb/sec}$$

$$\therefore \quad \Delta h = \frac{1500 \times 64 \times 0{\cdot}0025\ (18{\cdot}6)^2}{g \times \pi^2 \times (0{\cdot}3)^5}\ (16{\cdot}5 - 2{\cdot}9)\ 10^{-4} \text{ ft}$$

$$= 146 \text{ ft}$$

The pressure drop from this loss of "head" can be estimated from the $I(v)p_s$ correlation in Fig 5, as follows

$$\Delta h = 146$$

$$\therefore \quad \Delta h/p_s = 0{\cdot}097$$

At the well head p/p_s neglecting friction $= 0{\cdot}44$.

From Fig 5 a change in $\Delta h/p_s$ of 0·097 at $p/p_s = 0{\cdot}44$ corresponds to a change in p/p_s of 0·0196.

The pressure loss due to friction $= 0{\cdot}0196 \times 1500$ psi

$= 29$ psi

The friction loss in this case is small. If, however, it was large, then the value of p/p_s at the well head should be revised to obtain a more correct value of $I(v^2)/p_s$. This in turn will alter the value of p/p_s, and so the true value of p/p_s would have to be found by successive approximation.

An alternative method of estimating approximately the pressure drop due to the loss Δh is by using the ρ *v.* p/p_s correlation in Fig 7. From this graph at the well head pressure, neglecting friction, $p/p_s = 0{\cdot}44$ and $\rho = 28{\cdot}2$ lb cu ft.

Hence the pressure drop (assuming that the density is uniform over the small change in pressure) $= 28{\cdot}2 \times \frac{146}{144}$ psi

$= 28{\cdot}5$ psi

(b) Pressure Loss in the Surface Pipeline

The pressure loss along a pipeline is given by equation (2) as follows

$$144 \int_{p_1}^{p_2} \rho dp/p_s = \frac{64\ Fw^2\ L}{g\pi^2 D^5\ p_s}$$

which can be written in the form

$$I(\rho_2)/p_s - I(\rho_1)/p_s = \frac{64\ Fw^2\ L}{g\pi^2 D^5\ p_s}$$

At the well head

$$p/p_s = 0{\cdot}421$$

$$\therefore \quad I(\rho_1)/p_s = 3{\cdot}05 \times 10^3 \text{ from Fig 4}$$

$$\therefore \quad I(\rho_2)/p_s = 3{\cdot}05 \times 10^3 + \frac{64\ 0{\cdot}0025\ (18{\cdot}6)^2 = 5280}{g\pi^2\ (0{\cdot}3)^5\ 1500}$$

$$= 3{\cdot}28 \times 10^3$$

From Fig 4

$$p_2/p_s = 0{\cdot}365$$

$$\therefore \quad p_2 = 0{\cdot}365 = 1500$$

$$= 548$$

$$\therefore \quad p_1 - p_2 = 83$$

The pressure drop along the pipeline $= 83$ psi

PROBLEMS ASSOCIATED WITH THE MIGRATION OF OIL IN "SOLUTION"*

By G. D. HOBSON† (Fellow)

SEVERAL years ago E. G. Baker suggested that migration of oil from a source rock to a reservoir rock takes place in "solution." The idea of oil migration in solution was not new, but Baker gave more detailed consideration to various points than had been given before. The hydrocarbons were visualized as being "solubilized" by soaps in the presence of salt. Furthermore, selective "solution" was later thought to be important, leading to the occurrence of certain types of compounds in fairly constant ratios in crude oils.[1]

Migration in "solution" would remove one of the difficulties which seem to be associated with the hypothesis of primary migration of free oil droplets. It does, however, raise the questions of how and why oil is released from "solution" to give the free oil found in a reservoir rock. Baker suggested that dilution or change in temperature, among other things, may cause release. His basic hypothesis is still *sub judice*, and hence it seems worthwhile to examine some of the possibilities with respect to the matter of release, for thereby the fundamental problem of how an oil accumulation is formed may become better defined.

Release by Drop in Temperature or Pressure

Release by drop in temperature and/or pressure raises several problems.

1. The appropriate temperature or pressure might be attained in a rock other than a potential reservoir rock.‡ Should this occur the oil released must be viewed as lost, or if it is to become part of an accumulation the problem of the movement of free oil through a fine-pored rock must be faced. Attention was drawn to this difficulty inherent in the idea of primary migration of oil in solution some years before Baker's hypothesis was put forward.[4] The difficulty would be the same whether decrease or increase in temperature or pressure were the cause of the release.

2. A drop in pressure or temperature might occur only late in the geological history of an area. At that stage compaction of the fine-grained rocks might be far advanced, and under such a condition little or no flow owing to compaction would be proceeding. The oil "solubility" is low, and hence it is difficult to visualize a lens of reservoir rock having a considerable proportion of its pore space filled with oil if release occurs late.§ Even if some screening mechanism holds back any soap–oil complexes which have entered the reservoir rock, it seems likely that this difficulty would not be removed; there might be a greater amount of oil than without a screening mechanism, but not necessarily a high proportion of oil in body of reservoir rock considered as a whole.

The reasons for suggesting that any drop in pressure might occur only late in the history of an area arise from a consideration of the mechanism of compaction and the likely trend of events.

From a porosity/depth curve for a clay or shale series (Fig 1) it is possible to build up a plot of volume of pore space *v.* depth (Fig 2), because the area under the porosity/depth curve is proportional to the volume of pore space. For convenience, increase in pore space has been measured from the surface downwards. This curve gives the water content of a column of compactible sediment, say, 100 or 500 ft thick, which has just been deposited and is assumed to obey the porosity/depth curve. If this column of sediment is then buried by similar deposits¶ and has no water entering its base, it is possible to follow the behaviour of the water and the sediment which were just at the top of the column before its burial. For any depth of burial of the base of the column an interval can be read off on the depth scale of Fig 2 such as will give the same volume of water as was present in the column at the time its formation was just completed. This will define the position relative to the base of the column that tagged water representing the original top would have reached for the given burial of the base (it is assumed that the moving

* MS received 8 November 1960.

† Imperial College of Science and Technology.

‡ Bray and Evans [2] refer to the possibility of petroleum-like hydrocarbons having migrated from source sediments into a fine rock. Baker [3] inferred that these are present as free oil, but it is not clear that free oil is necessarily implied by Bray and Evans' statement.

§ For various reasons it is extremely difficult to demonstrate that a lens was and is effectively isolated by very low permeability material in all directions. However, F. M. van Tuyl and B. H. Parker (*Colo. Sch. Min. Quart.*, 1941, **36**, 157) state that "In a few instances . . . there is evidence of isolation of porous zones . . .," and they also refer to "inclosed reservoirs . . . largely or completely filled with oil. . . ." If isolated, oil-charged lenses do not exist, then some of the arguments in the present note must lose their force.

¶ For present purposes there is no need for the entire succession to be of this material, but only the sector immediately above the column under consideration; if that sector differs from the underlying material the figures will be altered.

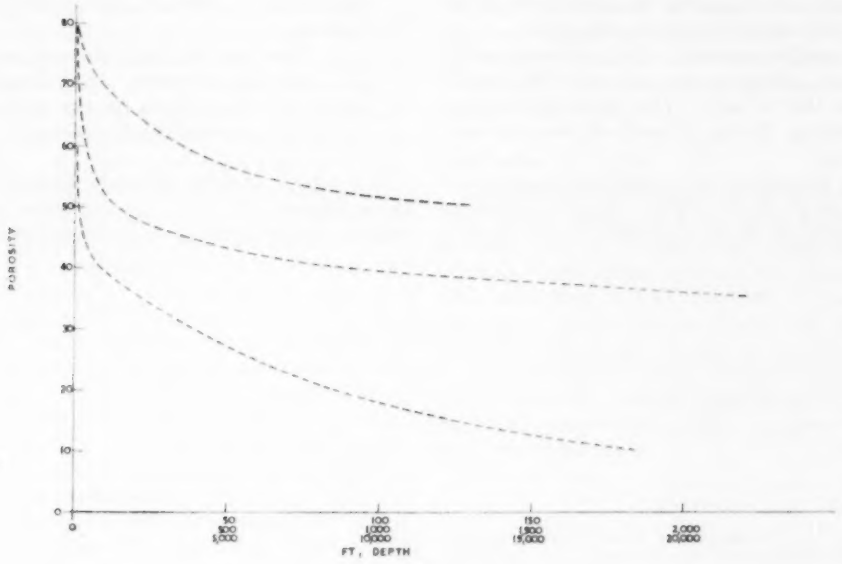

FIG 1

POROSITY–DEPTH CURVES (after Weller, J. M., *Bull. Amer. Ass. Petrol. Geol.*, 1959, **43**, 273–310)

The porosities are in percentages, and the three depth scales apply to the successive curves in descending order

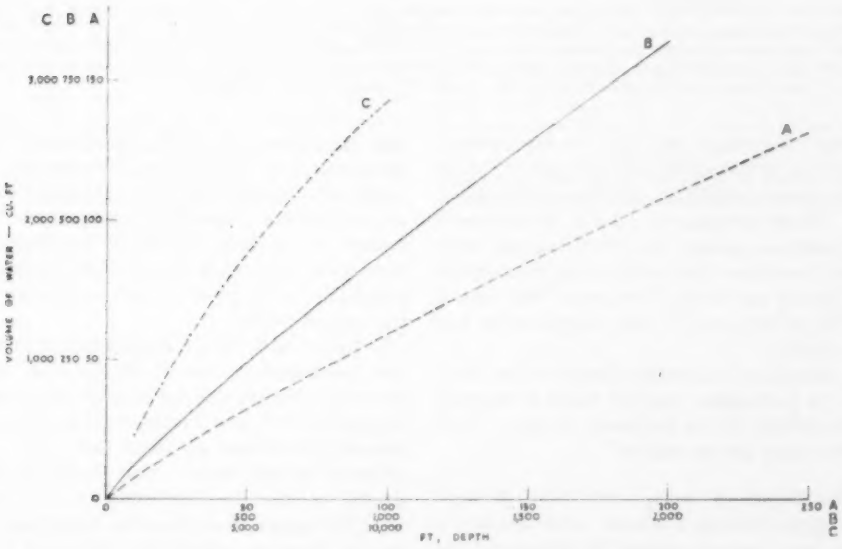

FIG 2

CURVES GIVING CUMULATIVE VOLUMES OF WATER *v.* DEPTH

The letters A, B, and C indicate the scales for each of the curves

water displaces all the water in the pores through which it passes; if it does not the movement of the tagged water will be greater than estimated).

Fig 3 summarizes estimates of the above type for two columns of sediment, one originally 100 ft thick and the other 500 ft thick. The positions of tagged sediment marking the top of each of these columns are also shown.

The above discussion on compaction assumes uniform distribution of fluid flow. Should conditions exist which give rise to focusing of flow on a small or large scale the conclusions will have to be modified in detail: the rise of the water will be greater in focal areas than is shown in Fig 3; outside such areas it will be less. Water entering the base of the sediment column will lead to a greater rise of the tagged water relative to the base than that predicted by the method described. Should any water flow out of the base of the column the relative rise of the tagged water will be less than shown.

It is now necessary to consider factors other than compaction; in particular, whether there is building up or general sinking of the sediment column. Two of the possible cases are as follows:

(*a*) The depth of water over the sediment remains approximately constant, with additional sediment being accommodated by sinking of the base of the deposit. If this condition holds it appears that, as sedimentation proceeds, the tagged water, although rising relative to the sediment with which it was originally associated and relative to the base of the column, is actually sinking in relation to sea level and having the pressure on it increased; its temperature will also be rising.

(*b*) The base of the sediment remains fixed with respect to sea level. In this case the tagged water will rise relative to sea level and it will move into zones of lower pressures.

In practice, for thick sediment columns, and during the sedimentation phase, the condition indicated by case (*a*) is more likely to be approached than that of case (*b*). However, in the uplift and erosion phases, irrespective of compaction phenomena, the tagged water will be rising into zones of lower pressure, but, as noted earlier, this will be comparatively late in the history of an area. Alternations of phases of sedimentation and uplift and erosion would lead to complications in the pressure and temperature history of the tagged water.

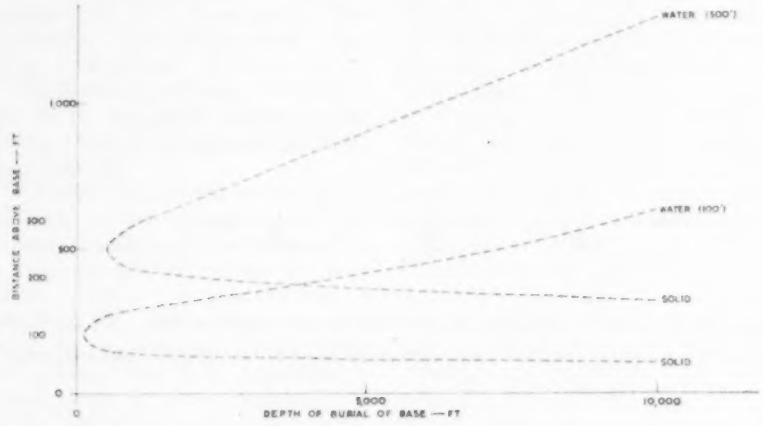

FIG 3

The curve labelled "Water (500')" shows the position of tagged water, which was just at the top when 500 ft of compactible sediment had been laid down, as the base of the column of sediment is buried more and more deeply. The associated curve labelled "Solid" gives the corresponding position of sediment which was initially associated with that water. The right-hand column of figures shows the distances. Similar curves are shown for water and sediment which were at the top when 100 ft of deposit had accumulated, the distances being shown by the left-hand column of figures.

A by-product of the consideration of the compaction mechanism is the conclusion that, although the porosity of newly-deposited sediment is the same, the proportion of "new" water included in the top of the deposit diminishes as more and more compactible sediment is laid down. This would mean that there would be less complete extraction of hydrocarbons from the upper than from the lower part of a source rock if there is overall an excess of hydrocarbons which are potentially capable of being "solubilized."

Release by Dilution or Change in Salinity

If migrating water with "solubilized" oil should enter a reservoir rock diffusion or mixing would

reduce the soap concentration, provided that the reservoir rock water does not contain as much soap as the water entering from the source rock. Dilution is stated to release "solubilized" oil. The degree of dilution possible would depend, among other things, on the volume of flow into the reservoir rock by compaction and on the volume of pore space in the reservoir rock. As compaction continues, the attainable degree of dilution would diminish unless faulting allows access to additional water or erosion permits the entry of meteoric water into the reservoir rock. The latter conditions could arise in some cases, but by no means generally. The volume of water in a small lens might not be enough to dilute much soap solution adequately, and as a result the release of sufficient oil to fill a substantial proportion of its pore space appears unlikely. It seems undesirable to postulate a release mechanism or, indeed, a hypothesis on the origin of oil, which cannot be applied equally well to explain the amounts of oil found in limited and in extensive reservoir rocks.

The water associated with oil in reservoir rocks is commonly more saline than sea water. Should this condition be a consequence of concentration processes operating in the sediments, it may be wondered whether a "salting-out" mechanism would release "solubilized" oil. Baker mentioned the possibility that the salinity might be a factor in the release mechanism.

In the case of some oil accumulations it has been suggested that the reservoir rock is also the source rock.[5] Dilution would be possible and progressive in such circumstances by water entering from adjacent compacting sediments, provided that it contains less soap than the connate water in the reservoir rock. In the absence of a filtration effect some of the "solubilized" oil would be displaced into nearby fine rock by compaction fluids. On the other hand, should "salting-out" be the means of effecting oil release, it could occur in this case also. Thus, if there are instances of oil formation in a reservoir rock they would appear to be comparable in many respects, so far as the release mechanisms discussed here are concerned, with cases where the source rock is not the reservoir rock.

Conclusions

According to the preceding discussion, it appears that neither change in pressure or temperature, nor dilution, can be accepted as a general means for releasing "solubilized" oil to give an oil accumulation. This conclusion cannot, however, be considered, in the light of present knowledge, to preclude the possibility of primary migration of oil in "solution." It must not be overlooked that acceptable hypotheses on oil origin and migration must be capable of accounting for the proportions of the total reservoir rock pore space occupied by oil.

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[3] Bray, E. E., and Evans, E. D. *5th World Petrol. Congr.* 1959, preprint.
[4] Hobson, G. D. "Some Fundamentals of Petroleum Geology." London: Oxford University Press, 1954. P. 77.
[5] Levorsen, A. I. "Geology of Petroleum." San Francisco: W. H. Freeman and Co., 1954. Pp. 510, 512, 514.

ADDENDUM

Since the manuscript was submitted information has come to light on three points. (1) The paper by Bray and Evans has been published in *Geochimica & Cosmochimica Acta*, Feb 1961, **22** (1), 2–15. (2) K. O. Emery and S. C. Rittenberg (*Bull. Amer. Ass. Petrol. Geol.*, 1952, **36**, 735–806) referred, amongst other things, to the reduced amount of additional water incorporated in the upper part of a column of compacting sediment. (3) G. E. Crosby and R. J. Cochran (*J. Petrol. Tech.*, Sept 1960, **12** (9), 39–41) have described a 38-acre lens which had oil in a substantial proportion of its pore space.

OBITUARY

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HARDLY two years after he retired from the chair of Chemical Technology at the Technical University of Delft, which he held for over 40 years, Professor Waterman, Honorary Member of the IP, passed away to the great regret of his many friends in his own country and far beyond its borders. In his more than 500 articles and 15 books he looked restlessly for the simple general characteristics of the many chemical and physical processes which he and his pupils investigated in the course of the years. The very last book he published was called "Process Characterization"; it was to be more or less his scientific testament.

In petroleum technology he introduced his famous "ring-analysis," but he produced similar graphical–statistical methods for the investigation of coal, fatty oils, silicates, and silicones. His 50 patents covered the results of his work on high-pressure hydrogenation, high-vacuum distillation, hydrogenation of fatty oils and fats, polymerization of ethylene, and the like. He worked on the manufacture of synthetic fibres from rubber and sulphur dioxide, discovered a cold-diffusion process for the extraction of sugar from beet, continuous polymerization of drying oils using sulphur dioxide as a catalyst, continuous styrenization of linseed oil using iodine as a catalyst, and many other problems.

But even such a list of important achievements describes only part of Waterman's personality. His scientific enthusiasm knew no bounds, his life was a compound of active work and leadership in his laboratory and many journeys to congresses and commissions both within and far beyond the boundaries of his native country. He was an inspiring teacher for a multitude of students, and the number of those who studied under his guidance and later reached professorial rank shows how he not only taught them the bare facts of chemical technology but imbued them with the true ardour for scientific research.

Not only the IP but many other institutions and universities honoured Waterman during his lifetime, but at heart he always remained a humble and modest man, a steady and honest scientist, always busy reading, discussing, and teaching the latest facts and discoveries at the earliest possible moment. He took a most lively interest in his pupils, inviting them home and constantly interesting himself in their careers when they had left the university. In this way he truly formed a school of pupils who will carry on where he left off. His many friends in the IP who have often met him, heard him lecture, or have read his publications will regret the loss of a true friend whose influence in the world of petroleum will be felt for many a year to come.

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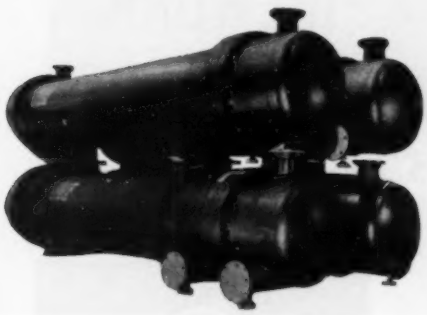

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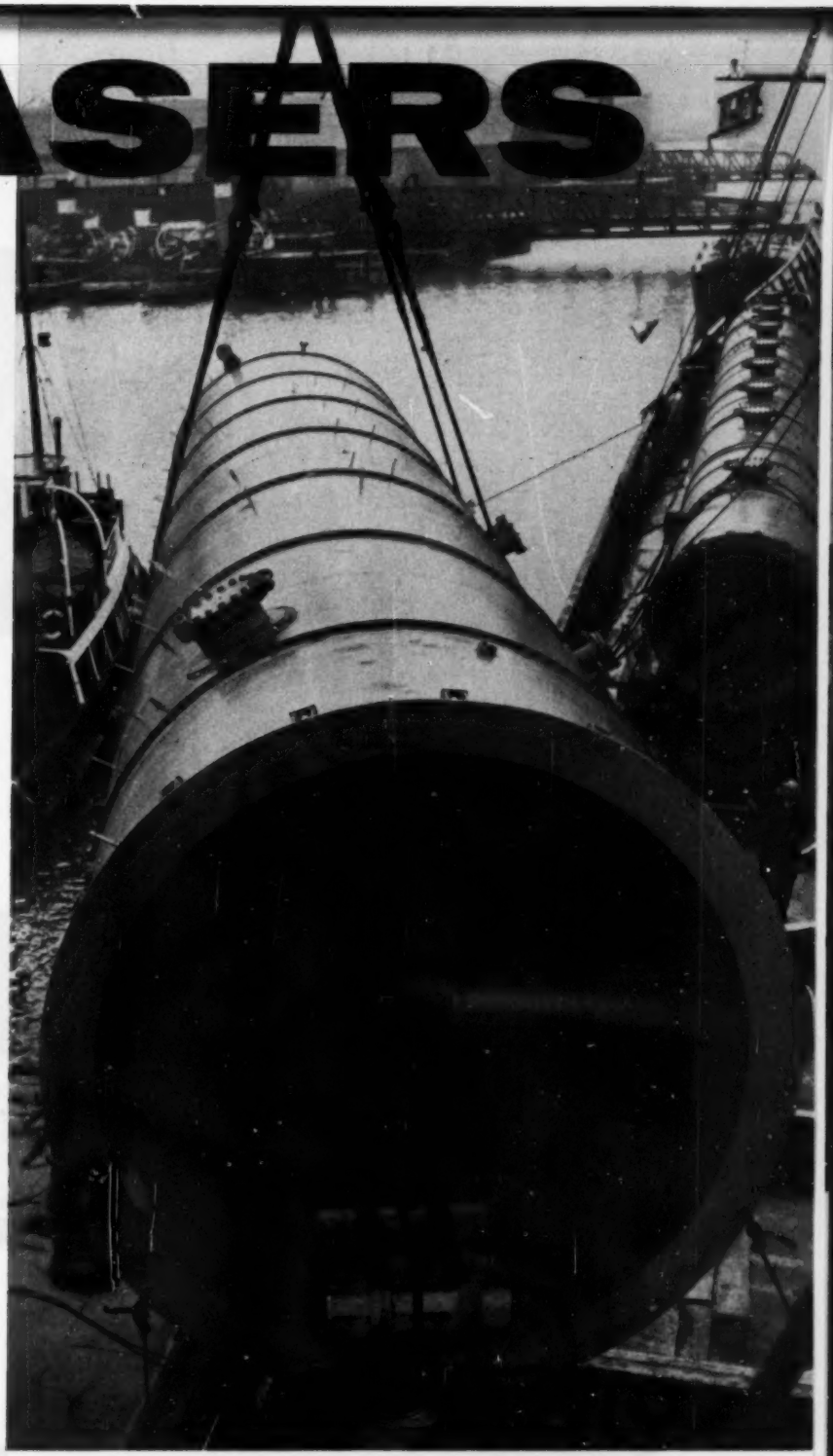

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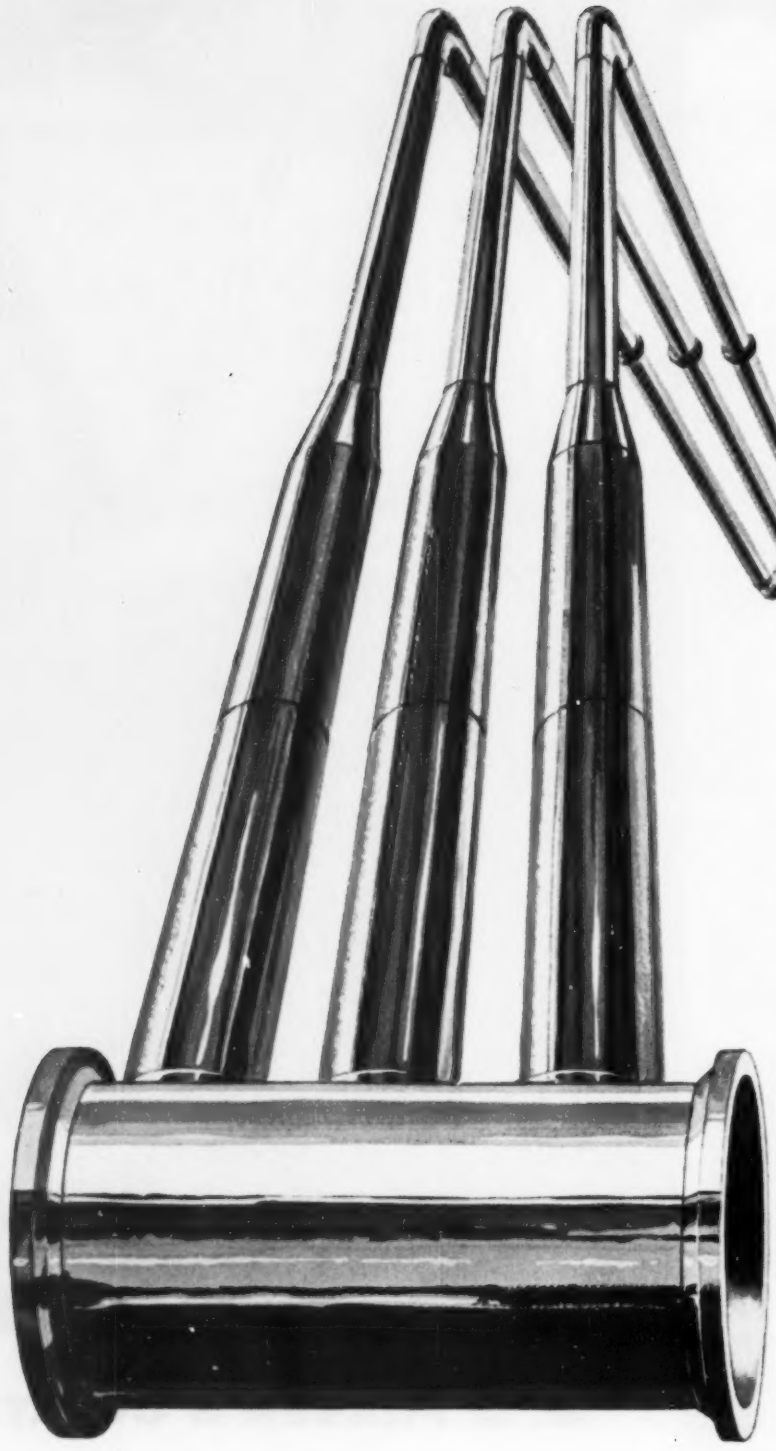

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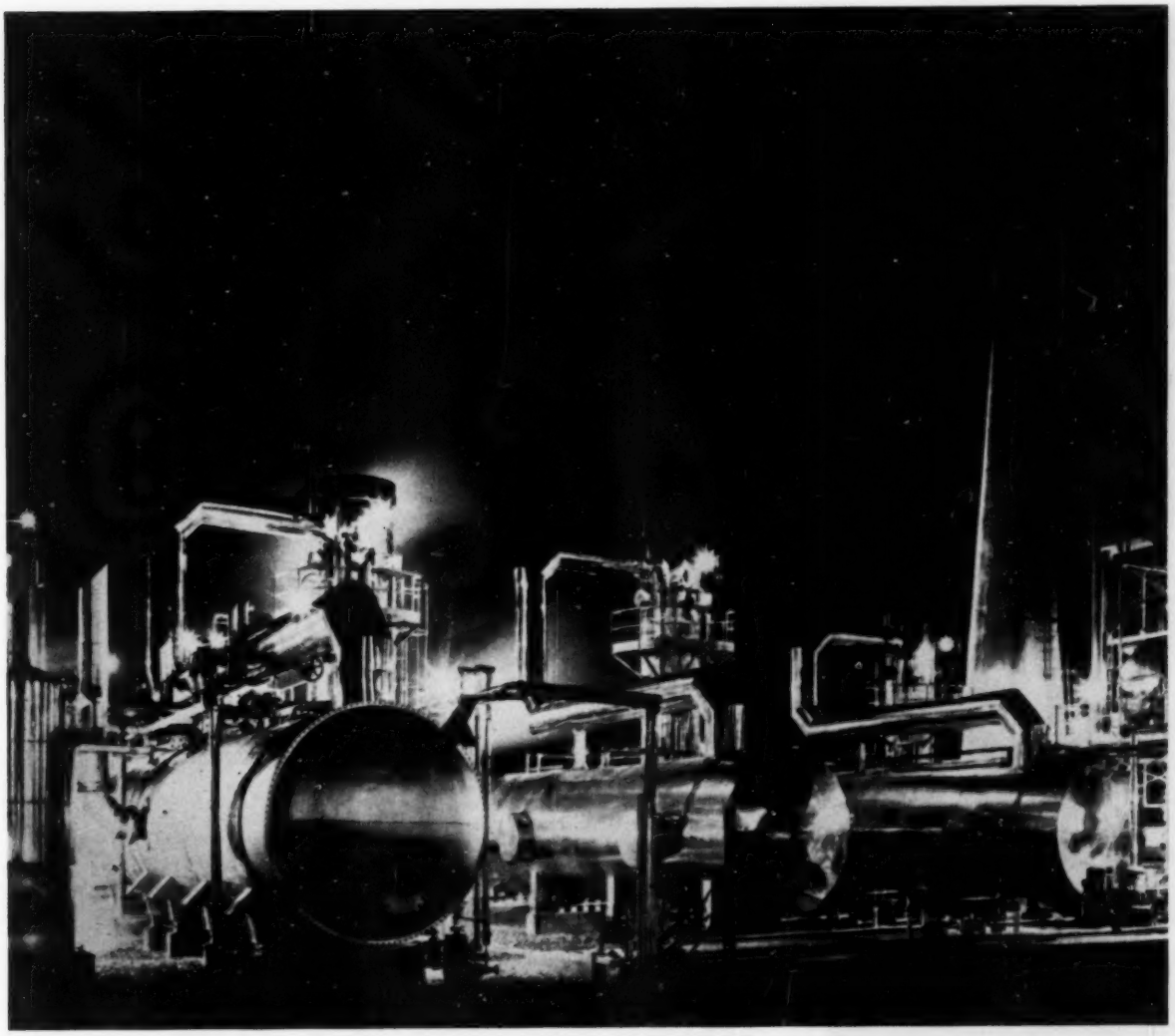

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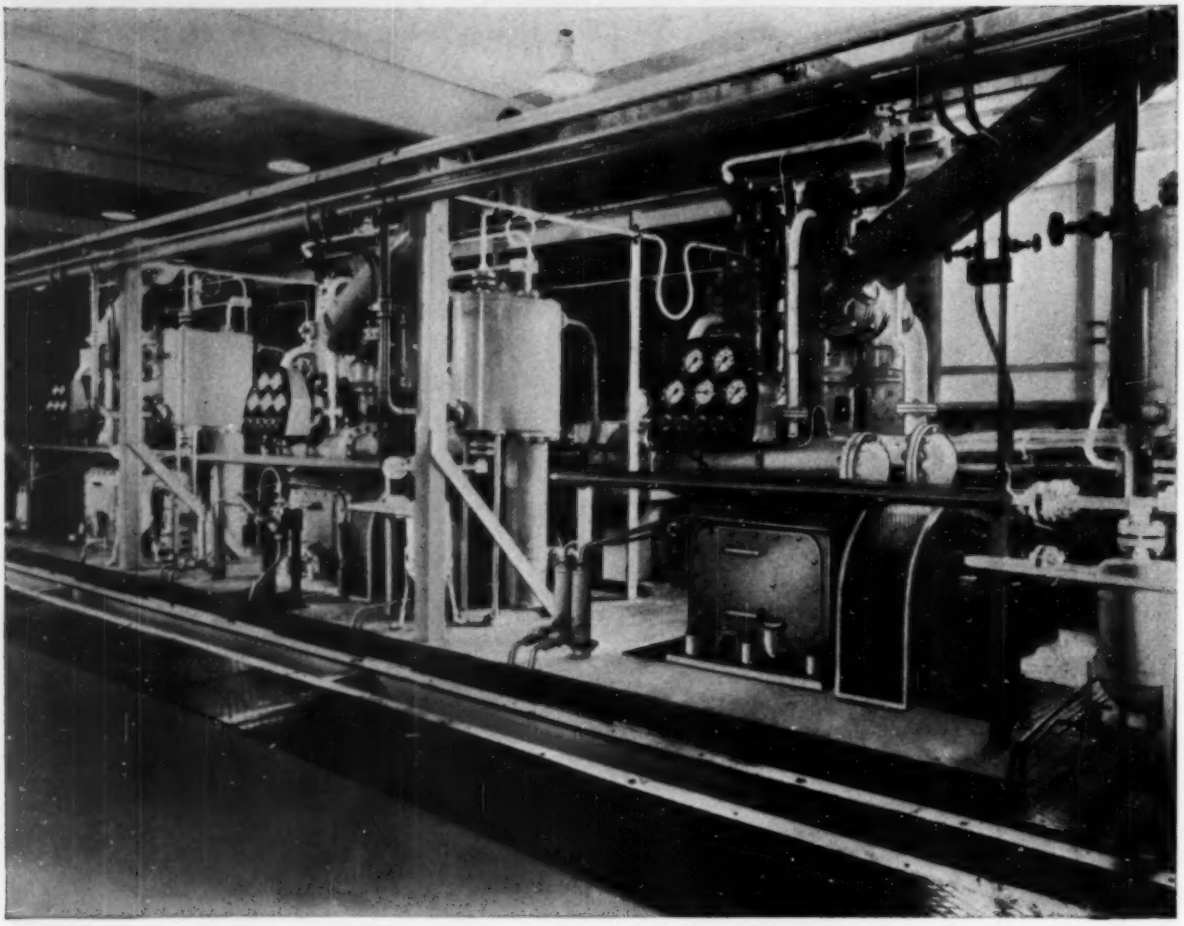

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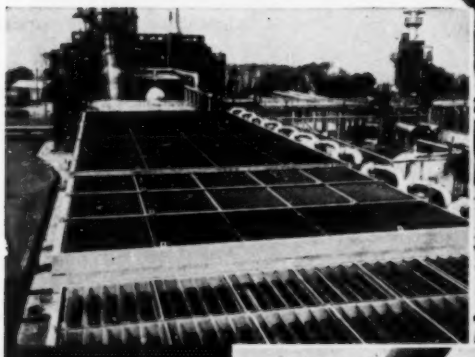

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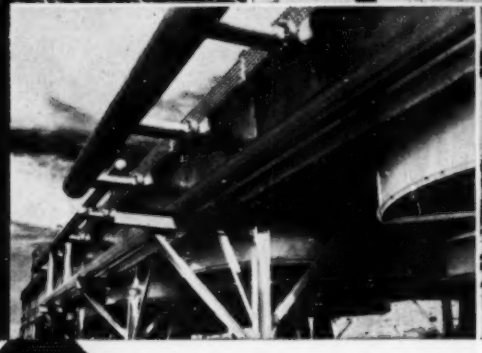

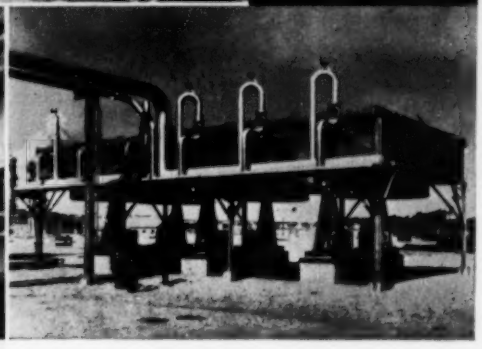

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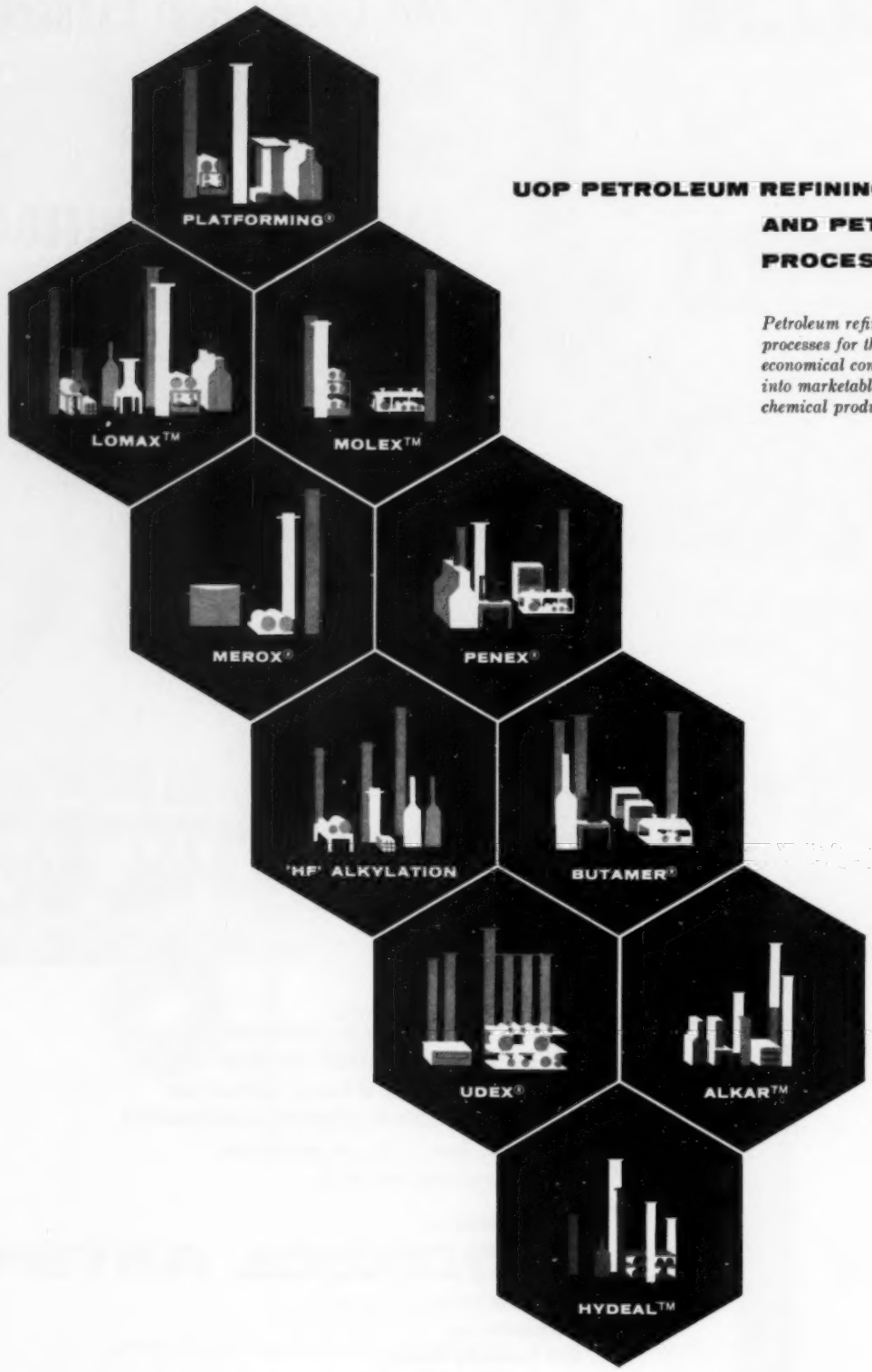

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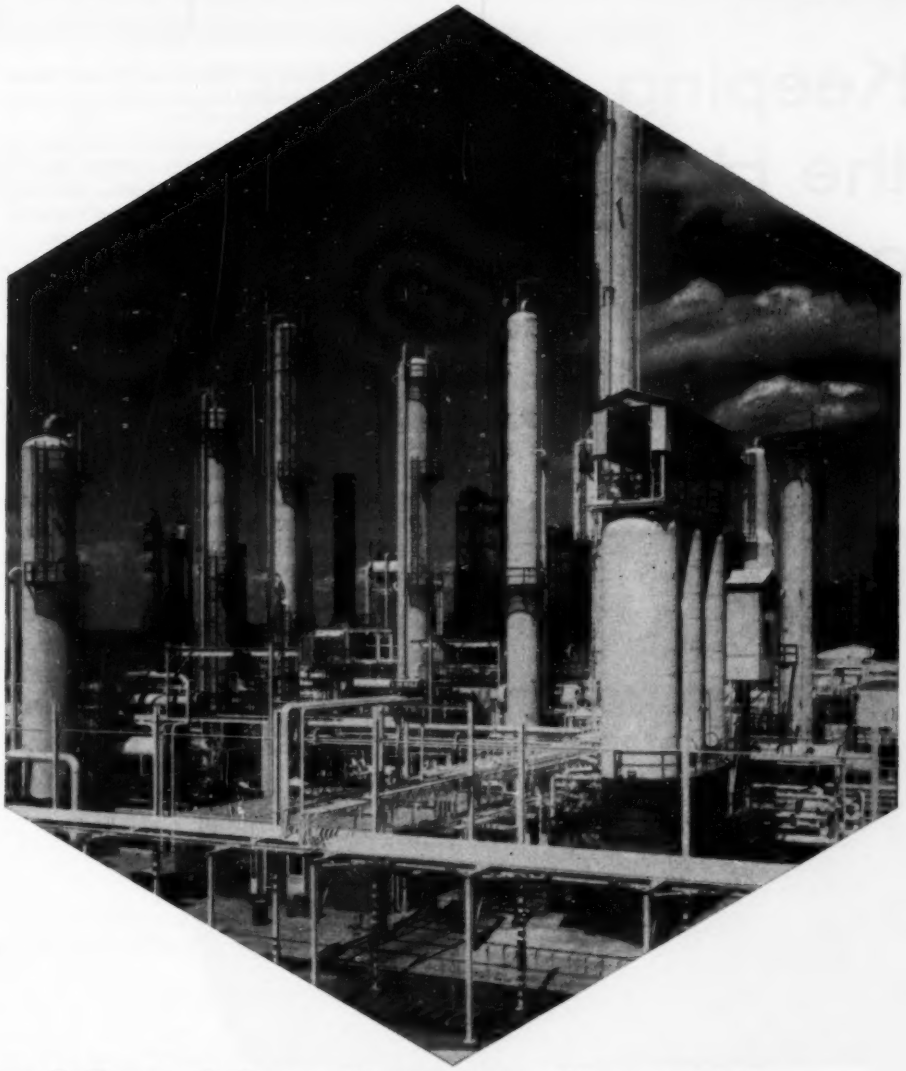

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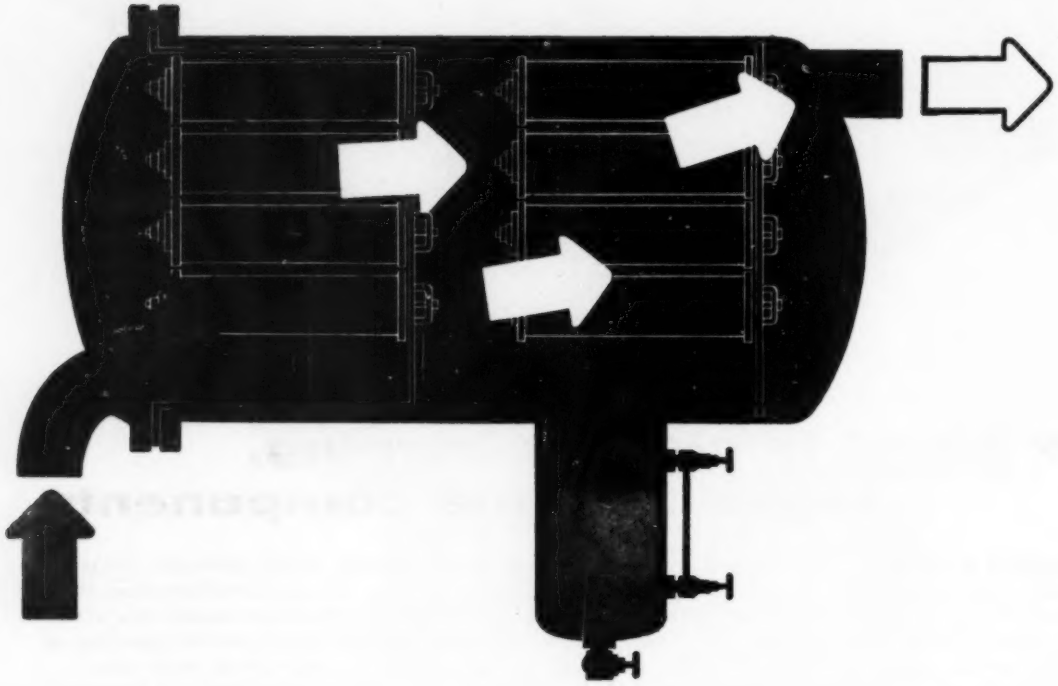

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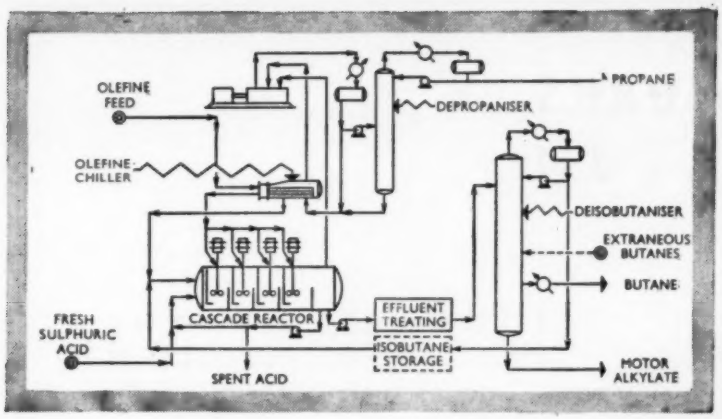

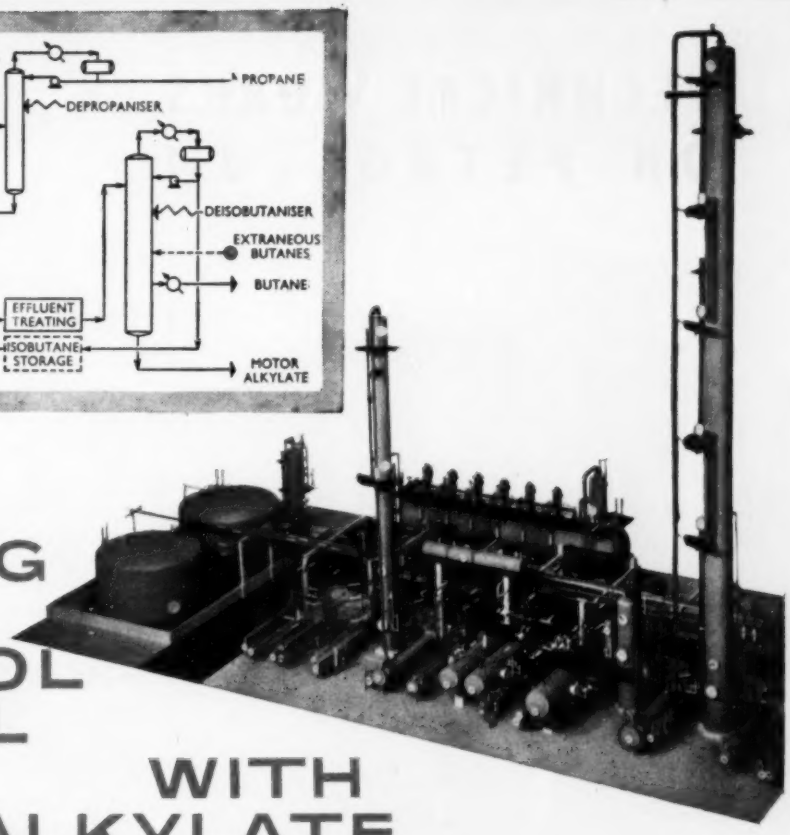

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(Sandbrook, Metcalf & Co. Ltd)
Babcock & Wilcox Ltd . . . Apr.
(S. H. Wright & Co. Ltd)
Baker Oil Tools Inc. . . . . Apr.
(John A. Ripley Advertising Inc.)
British Oxygen Co. Ltd, The . . Jan.
(F. C. Pritchard, Wood & Partners Ltd)
Peter Brotherhood Ltd . . . iv
(J. Peers & Associates Ltd)
Robert Cort & Son Ltd . . . Jan.
(Granthams of Reading)
A. F. Craig & Co. Ltd . . . v
De Havilland Aircraft Co. Ltd . . Apr.
(Samson Clark & Co. Ltd)
Dorr-Oliver Co. Ltd . . . . Mar.
Foster Wheeler Ltd . . . . Apr.
(Wm Hopwood & Co. Ltd)
Foxboro-Yoxall Ltd . . . . Mar.
W. J. Fraser & Co. Ltd . . . i
(Technical Advertising Service)
General Refractories Ltd . . . Feb.
(John Mitchell & Partners Ltd)
Matthew Hall & Co. Ltd . . . xi
Hughes Tool Co. . . . . Apr.
(Foote, Cone & Belding Ltd)
Intermit Ltd . . . . . Apr.
(Sandbrook, Metcalf & Co. Ltd)
Kellogg International Corporation . ix
(Reynell & Son Ltd)
Marston Excelsior Ltd . . . ii
(Clifford Martin Ltd)
Mechans Ltd . . . . . Apr.
(James Jack Advertising Ltd)
Newman, Hender & Co. Ltd . . Mar.
(Hamill Toms Ltd)
Parsons Powergas iii
Procon (Great Britain) Ltd . . . Apr.
(Tobias, O'Neil & Gallay Inc.)
Pyrene Co. Ltd . . . . . Jan.
(Nelson Advertising Service Ltd)
Simmonds Aerocessories Ltd . . viii
(C. R. Casson Ltd)
Solartron Electronic Group Ltd . . Mar.
(P. A. May & Partners Ltd)
Universal Oil Products Co . . vi & vii
(Tobias, O'Neil & Gallay Inc.)
Henry Wiggin & Co. Ltd . . . Apr.
(Technical & General Advertising Agency Ltd)

MATTHEW HALL

Glasgow
Cape Town

Manchester
Welkom

Bristol
Bulawayo

Johannesburg
Salisbury (Central Africa)

Germiston
West Indies